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EVALUATION OF PROTOTYPE LANDFILL COVER LYSIMETERS

R. A. C. PROJECT NO. 426C

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SUMMARY

This report presents the results of monitoring four (4) prototype landfill lysimeters through a full calendar year in an effort to evaluate the lysimeter's effectiveness as a tool in measuring landfill cover infiltration. Annual infiltration measured by lysimeters ranged from 18 percent to 59 percent of the total precipitation which fell in the same period. It is the opinion of the study team that this wide range in infiltration estimates among lysimeters is a function of the different features present in each of the lysimeters rather than a direct result of the variability in infiltration rates possible across a landfill cap even with consideration given to the non-homogeneity of the landfill in the vicinity of the lysimeter installations.

The lowest value for percent infiltration is regarded as being the estimate most representative of the entire landfill. Analysis of well level hydrographs generated by some of the lysimeters showed periods where the rate of infiltration was quite rapid, indicating the presence of preferential flow paths. Quantities of inputs during the period of rapid filling were also quite large on those lysimeters fed by up-gradient surface and subsurface water sources. The preferential flow paths are thought to be a consequence of the presence of the lysimeter rather than an effect of variations in landfill cap characteristics.

To improve the ability of the lysimeters to obtain representative infiltration estimates, a number of alterations to lysimeter design and construction are proposed. The key alterations include, taking additional precautions at preventing preferential flow paths along lysimeter components, strict adherence to installation protocol to minimize differences between the portion of the cap above the lysimeter and the surrounding landfill cap and installation of a more sensitive storage zone or at least a more accurate approach to collecting infiltration data from the lysimeters.

ACKNOWLEDGMENTS

The work to be described in this report was undertaken by Ecologistics Limited in association with an advisory group based at the University of Guelph. The following are members of the study team:

Principal Investigators:	J.H. Cuthill - University of Guelph K.J. McKague - Ecologistics Limited
Advisors:	W.T. Dickinson - University of Guelph

P. Groenevelt from the Department of Land Resource Science at the University of Guelph provided insight into physical processes and was very helpful when asked for information. R. McBride of the same department also made helpful suggestions and aided in response curve analysis.

C.A. Bostock, G. Hughes and E. Reid of the Ontario Ministry of the Environment all contributed to the quality of this report through their interest and direction in the study.

Personnel with the Regional Municipality of Peel provided the logistical support needed and were very helpful in providing the necessary maintenance for the study site.

Mr. P. McLennan of Ecologistics Limited was particularly valuable to the study team as a field assistant and in preparing study data for analysis purposes.

1.0 INTRODUCTION

Controlling the rate of leachate production so that its collection and treatment is manageable is a major consideration in the design and approval of municipal solid waste landfills. Varying views exist among those familiar with landfill technology as to the portion of leachate production that can be attributed to infiltration through the landfill cover material, especially when soils of differing textures are used in their construction. Having the capability to monitor and predict the rate of leachate generation as a consequence of the landfill cover's characteristics would be useful in sizing and costing site collection and treatment facilities for leachate. As well, having monitoring capabilities through direct field measurements could ensure that the cover continues to perform as designed throughout its life and also could indicate a need for maintenance if performance expectations for the cover are not met. Finally, long-term monitoring of landfill cover infiltration on sites possessing covers of differing soils could ascertain whether it is necessary and cost-effective to select and import soil materials which, in theory, will reduce infiltration but which in practice may not be significantly more effective as soil structure and macropores develop and as the materials dry and shrink, forming cracks.

1.1 Background

Environment Ontario has, to date, initiated a couple of studies aimed at quantifying infiltration through landfill covers with particular attention being given to the development of a landfill cover lysimeter that is capable of making repeatable and consistent direct infiltration measurements. The first study completed on behalf of the Ministry of the Environment entitled "Field Measurement of Infiltration through Landfill Covers" (Gartner Lee Associates Limited, 1985) described the design, implementation and testing of two prototype lysimeter designs. In this study, little correlation was found to exist between the individual lysimeters on an event by event basis as well as on a seasonal basis. The correlation between the lysimeters tested on a time-averaged monthly basis was, however, relatively high although even then a high degree of variation was noted during the summer months when cover soils are dryer.

Building on the experience obtained from the installation of this set of first generation lysimeters, the Ministry of the Environment developed a second generation prototype. The design changes incorporated into this new lysimeter were made in an effort to produce a measurement tool that was simpler in design and construction while at the same time more sensitive to inputs from individual rainfall events. A total of six lysimeters of the same basic design were to be installed in order to improve confidence in the repeatability of the design through conducting a comparison of results among the lysimeters.

The second set of prototype lysimeters were installed in August of 1987. Ecologistics Limited was contracted by the Ministry to monitor their performance. It was anticipated that, through monitoring the lysimeters, an improved understanding of the infiltration process on landfill cover systems would be achieved and would be important in assisting the Ecologistics study team in their additional task of developing criteria for modelling of the process.

Through monitoring of the lysimeters, it soon became apparent that they were not functioning in the manner expected. Erratic fluctuations in water storage readings were observed. Details concerning the causes for water level fluctuations and the modifications made to eliminate the problem were outlined in a report prepared by Ecologistics Limited (1989) entitled "Erosion of Municipal Solid Waste Landfill Covers".

Several months were required before the source of the problem was pin-pointed and modifications were made to the installed units to make them operational. Consequently the prototype lysimeters did not even appear to be operational until the spring of 1988. Collection of infiltration data for an entire calendar year was considered necessary in order to observe and evaluate the lysimeter's operation through all four climatic seasons. It was anticipated that the effects of such things as soil moisture content, evapotranspiration, frozen and thawing soils could all be best evaluated through viewing lysimeter response over an entire year. Thus, to obtain data covering these seasons, monitoring of the lysimeters was extended to May of 1989. This document reports on the observations made and provides an evaluation of this second generation prototype lysimeter's response and performance through an entire year's climatic cycle. Limitations in this prototype's design along with suggestions for improvement are also presented.

1.2 Study Objective

The objective of this study was to undertake uninterrupted monitoring of the existing modified prototype lysimeters though an entire year in order to provide the database necessary to evaluate their suitability as an infiltration measurement tool on landfill covers. To achieve this objective a number of goals were established and can be summarized as follows:

1) To collect and analyze stage recorder data from the lysimeter's monitoring well and ascertain whether there is a correlation between this data and daily precipitation data.

2) To determine the effect of summer desiccation periods on fall infiltration rates.

3) To distinguish from the annual proportion of through-cover infiltration, that portion which is attributed to the spring thaw months.

4) To determine the infiltration rates through the winter season.

During the projects undertaking it became apparent that it would be worthwhile to monitor the lysimeters' response to simulated rainfall inputs as well as to natural inputs. Consequently, a fifth goal was added to the list, that goal being:

5) To collect and analyze stage recorder responses resulting from known simulated inputs and ascertain whether there is a correlation between this data and the simulated rainfall amounts.

2.0 THE PROTOTYPE LYSIMETERS

2.1 Location of Lysimeter Installations

In 1987, personnel within the Waste Management Branch of the Ministry of the Environment developed a lysimeter design, building on the experience obtained in a previous study conducted for the Ministry of the Environment (Gartner Lee, 1985). Six prototypes of the design were subsequently installed at the Britannia Road Sanitary Landfill by M.O.E. and Peel region personnel.

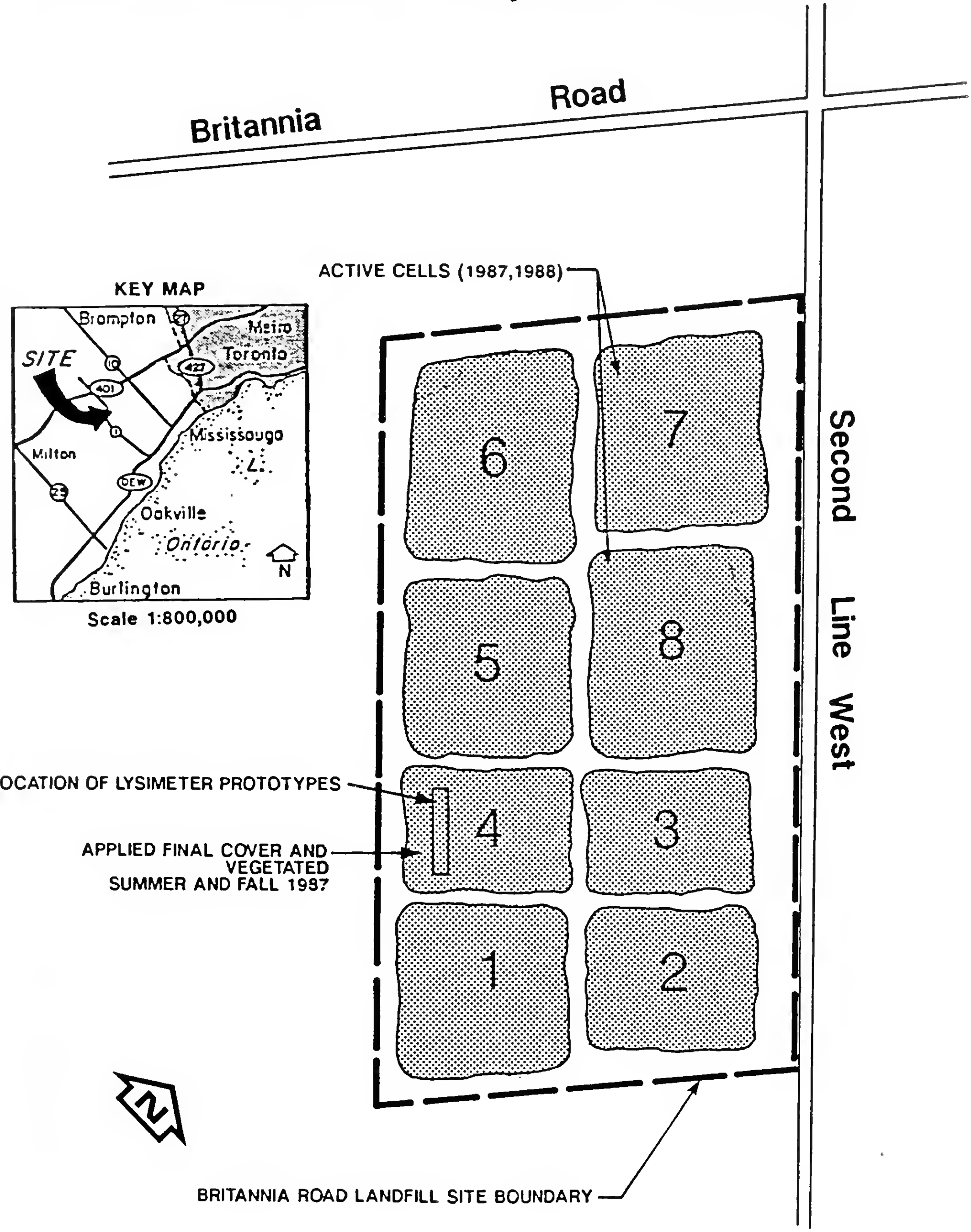
The Britannia Road Sanitary Landfill is situated on the second line west, 0.25 kilometres south of Britannia Road in the Mississauga East Credit Planning Area. The site is 82.4 hectares (206 acres) in size, of which 60 hectares (150 acres) are designated fill area. Operations commenced in January of 1980 and are expected to continue until 1990 under a Regional agreement with the City of Mississauga. The site is divided into 8 cells of approximately 8 hectares each. The lysimeters were installed on the west face of cell 4 as illustrated in Figure 2.1. The post-closure plan for the site is the "Britannia Links" golf course and consequently the topography of the area is irregular. The lysimeters were installed on a relatively uniform surface area where the slope is 2 to 3 percent. The area is best described as the mid-bench on a terraced slope and consequently receives moisture inputs from up the grade. A complete description of the installation procedure documented by M.O.E. personnel is in Appendix A of this report. In addition, a photographic record of the installation procedure is on record with the Ministry of the Environment.

2.2 Lysimeter Design

As stated previously, a lysimeter prototype was designed specifically for this research undertaking. In fact, one prototype, but with two different mediums for storage was designed. Henceforth, the lysimeter types will be distinguished from one another by referring to each by the material used for the storage zone. More specifically, they will be referred to as the "gravel type lysimeter" or the "drain tile type lysimeter". As illustrated in Figures 2.2 and 2.3, the lysimeter types are virtually identical in design with the exception of the depth of and material used for the storage zones; that being, 30 centimetres of gravel and 21 centimetres of drain tile, respectively. With the drain tile storage zone being approximately 9 centimetres lower than the gravel storage zone, the additional depth is compensated for by placing a greater depth of sand over the drain tile type lysimeter than was found in the gravel type.

The design of the lysimeters incorporated most of the recommendations cited in the literature. The data recording system was automated and care was taken to avoid preferential flow down liner-fill and well-fill interfaces through the liberal use of bentonite. The surface area, being 9.3 square metres, was large

FIGURE 2.1: Site Location for Lysimeter Installations



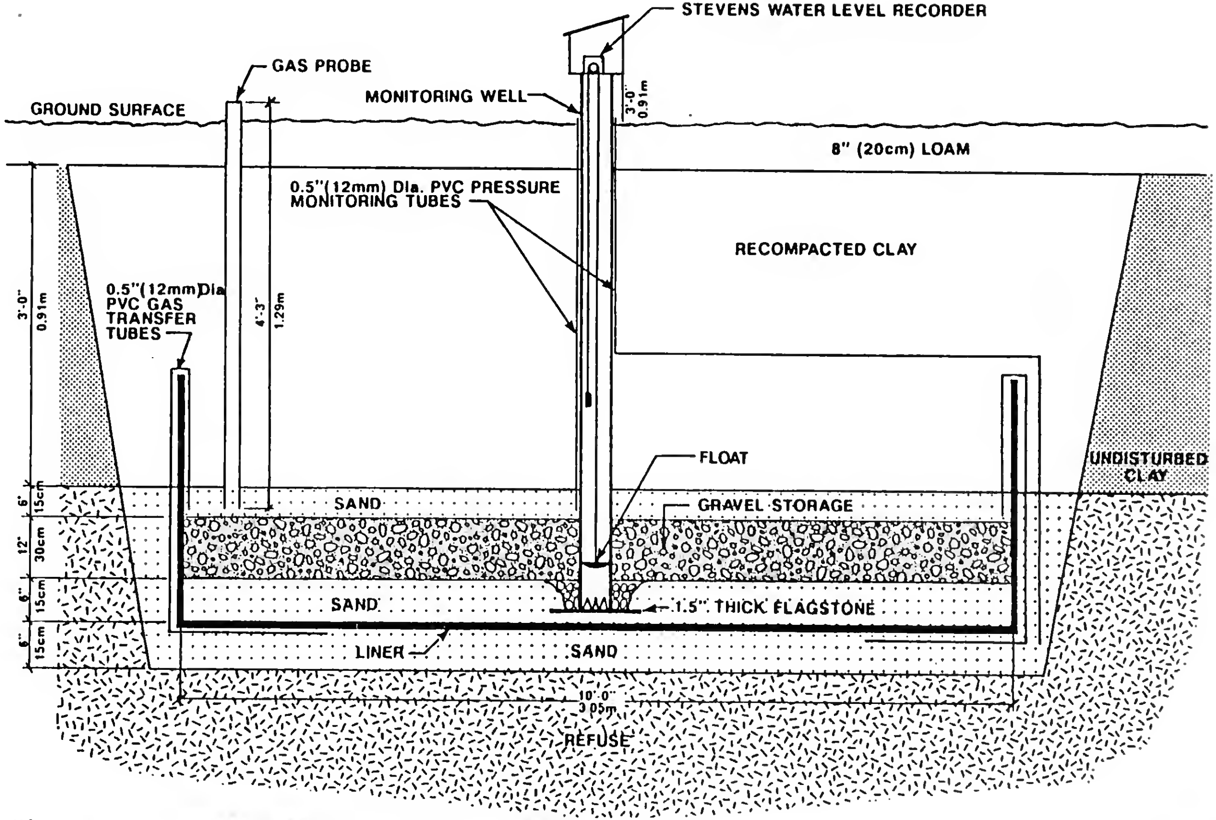
enough to be considered representative and each of the six lysimeters were situated on similar slopes with similar vegetation. The importance of reproducible results was acknowledged and therefore three of each lysimeter type were installed. Lysimeters numbered 1, 2, and 6 were the gravel type while those numbered 3, 4, and 5 were the drain tile type. The lysimeters were numbered in ascending order from south to north. A schematic illustration is included in Appendix A.

In brief, the precipitation or snowmelt that was not shed by the clay cap in the form of run-off, consumed by evapotranspiration, or stored in the loam cover or clay cap infiltrated the cover system and was captured below in the storage zone of the lysimeters. As the gravel or tile storage zone filled, Leopold Stevens water level recorders documented the change in stored water level. The design required that periodic monitoring be conducted and when necessary that the storage zones be pumped out to avoid over filling. Specifications required that the bottom of the well casing be serrated to facilitate a rapid transfer of water entering the monitoring well. The openings were to be a minimum of 2.5 centimetres long and 2.5 centimetres wide. The well was then to have a minimum of 5 centimetres of coarse gravel placed inside and an additional 15 centimetres of coarse gravel placed outside. In addition, all lysimeters were to receive methane transport tubes to help simulate decomposition gas conditions beneath the overlying clay cap and loam cover.

Upon inspection of the lysimeters after their installation it was noted that some adjustments were made to the original specifications during construction. While some of the modifications were documented in the installation report (Appendix A), others were not noted until a visual inspection was made. For example, it was found that the specified 5 centimetres of coarse gravel was not placed inside the monitoring well leaving the base of the well to consists simply of flagstone overlain with filter cloth. Locations and depths of storage zones and soil layers were also uncertain for survey notes were not kept of the elevations of the various layers during the installation. As well, only two of the six lysimeters had gas monitoring and exchange tubes installed, with only one of these seeing the installation actually being carried out to completion.

Initial monitoring of the lysimeters in the fall of 1987 and early winter of 1988 revealed that the lysimeters were not operating as expected. Water levels in the storage zones of all the lysimeters were fluctuating up and down considerably despite the fact that these were not losses from the storage zone. An explanation of these well level observations was eventually obtained upon comparison of well level graphs with atmospheric pressure readings for equivalent time periods. Well level charts were found to be the mirror image of the fluctuations shown by the atmospheric pressure charts. From this, it was concluded that the extreme water level fluctuations were the result of the presence of a trapped air layer between the water in the storage zone and the apparently impermeable overlying recompacted clay layer. While the previous Ecologistics Limited report entitled "Erosion of Municipal Solid Water Landfill Covers" (1989) describes in detail the steps followed to reach and verify the above hypothesis, the effective action taken to overcome this phenomenon entailed "venting" the lysimeter by drilling numerous

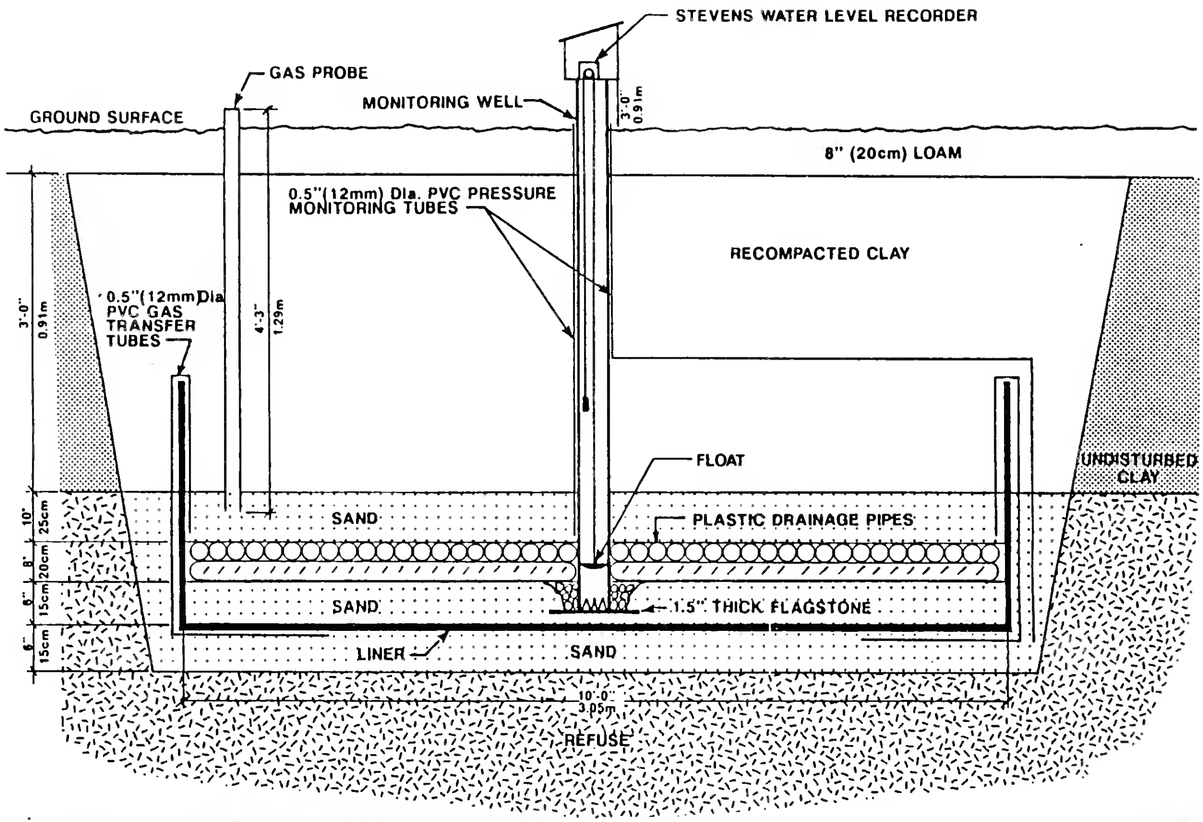
FIGURE 2.2: Gravel Type Lysimeter Cross-Section



NOTE: Gas monitors and equalize₀s installed in 2 of 6 lysimeters

Not to scale

FIGURE 2.3: Drain Tile Type Lysimeter Cross-Section



NOTE: Gas monitors and equalizers installed in 2 of 6 lysimeters

Not to scale

small holes into the side of the well casing within the region of the storage zone. This field modification was completed on all lysimeters by late April, 1988. Following this modification, lysimeter hydrographs responded as would be expected for a filling storage zone.

In addition to venting the lysimeters, the study team also opted at the same time to install galvanized steel barriers upslope of three of the lysimeters as a long-term means of determining whether surface run-off from upslope and/or subsurface interlayer flow was contributing inputs to the lysimeters' storage zone. These barriers were installed vertically into the loam cover and extended into the clay cap. They were installed on an angle and for a length sufficient to allow any water flow encountering the obstruction to be diverted outside of the lysimeter area. Installing the barriers consisted of digging a trench through the loam cover and then pounding the sheet steel into the clay cap a minimum of 5 centimetres. The trench was then back-filled. Only lysimeters 1, 3 and 5 received this barrier modification in order that comparisons could be made between their infiltration results and the untreated lysimeters to determine barrier effect (if any).

To assist in answering some of the questions concerning lysimeter configuration and the state of deterioration of the lysimeter materials, the Ministry of the Environment gave the study team approval to excavate one lysimeter of each storage type. Consequently only four (4) lysimeters remained for the full year analysis presented in this report. Upon excavation it was found that construction materials were still in good shape and that the thickness of the pertinent soil and storage layers were as indicated in the construction notes (within reasonable tolerances). As well, the actual size of the drain tile installed was confirmed. Measurements from the flagstone to the bottom of the designated storage zones were also made on the drain tile type lysimeter. Data collected was used to locate pertinent layer locations for the remaining unexcavated lysimeters by making the assumption that lysimeters having similar storage types were built identical to one another.

Finally, at the time of excavation, the elevations of the bottom of the well of the remaining lysimeters were determined, related to a permanent benchmark and documented.

2.3 Lysimeter Calibration

In September, 1988, following the field modifications, when the study team was confident the lysimeters were operating in a much more predicted and expected fashion, calibration of the storage zones was completed. Lysimeter calibration was necessary to relate the height of water in the monitoring well to the volume of water collected in the storage zone. Once calibration curves had been developed for each lysimeter, the lysimeters could be used to quantify that portion of precipitation which resulted in through-cover infiltration.

The calibration procedure consisted of first, defining a datum or initial water level. This task, while seemingly simple, proved difficult in itself due to the time required for the well's water level to reach static conditions following the addition or removal of water. This problem existed despite the considerations made in the lysimeter's initial design to encourage rapid draining to the well and the later addition of vent holes to encourage rapid air/water transfer. Due to the extremely slow recharge rate and relatively low water storage capacity of the sand layer underlying the storage zone, it was decided that a datum line be defined at this lower sand/storage zone interface. Without a surveyed description of the location of this boundary, the datum's distance from the base of the well was established through observations made when two of the lysimeters were excavated in the summer as described previously and through close monitoring of the well levels during the initial set of inputs.

Upon establishment of datum, the calibration procedure involved adding water to the lysimeter's storage zone through the monitoring well in 100 litre or 200 litre Increments. Following each addition of water, the well water level was measured. Water level readings were then taken In five minute intervals until three successive readings were found to be equal (within 1 millimetre) before more water was added. This helped ensure that the water level had approached steady-state conditions. This procedure continued for each 100 litre addition to the lysimeters until the input met or exceeded the capacity of the storage zone at which time the stage recorder was re-installed to monitor the final steps to equilibration. It was apparent when the storage zone had been filled, for there was a much more rapid rise in well level once water began to fill the overlying sand layer. Once the lysimeter storage area was filled at or above capacity, it was left to equilibrate for a period of two to six days. Following the period of equilibration the calibration procedure was reversed with the storage zones being pumped out in either 100 litre or 200 litre intervals. The same measurement procedure was used to consider the static condition of the well's water level.

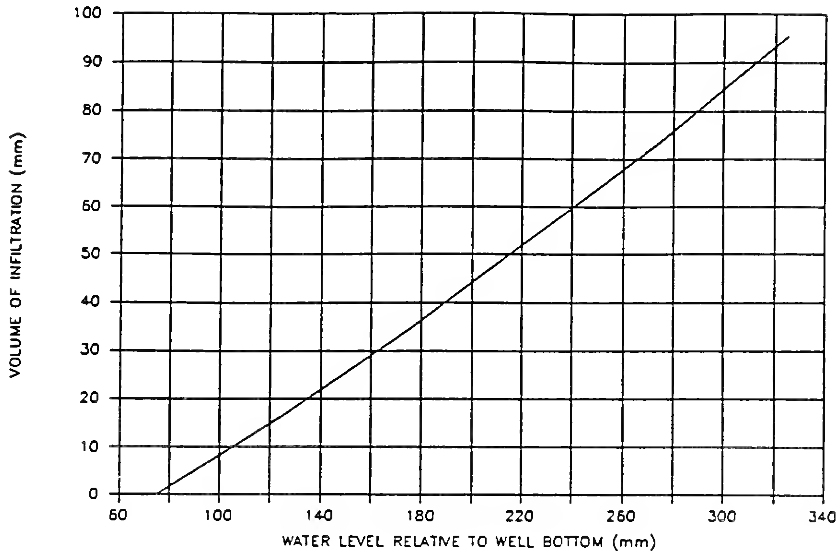
It became obvious both from the chart recorder results during the two to six day period between the "calibration in" and the "calibration out" and through comparison of the shape of the calibration curves resulting from both procedures that, while venting dramatically improved the storage areas' recharge rate to the well, there was still approximately a three day lapse in time until the well level reached fully static conditions. This phenomenon can be seen graphically in Figures B1 to B4 of Appendix B for each lysimeter. For the gravel type lysimeters less water was pumped out than was pumped in showing the gravel type to be slower in recharge response than the tile type. Note as well, the drop in well level for each lysimeter between the calibration "in" and the calibration "out" procedure. With the slow rate of recharge resulting in the production of two separate calibration curves, the next task involved developing a single calibration curve for each lysimeter. Two approaches were considered. The first approach consisted of simply connecting with a straight line the first or initial data point on the calibration "in" curve to the final data point on the calibration "out" curve. Thus the only two truly static points are used in preparing the calibration curve. While this may seem simplistic initially, it is probably relatively accurate and worth considering given that calibration was completed for the storage zone only and the

storage medium remained consistent, being either tile or gravel over a square surface area. It is realized that perimeter bulges in the storage liner and/or some slight inconsistencies in the storage medium would produce a calibration curve that is slightly off from being a straight line. However, given the configuration of the storage zone and the water level measurement tools and techniques used which could be read only to the nearest millimetre, this approach is probably suitable and was determined to be worth considering. The dotted lines presented in Figures B1 to B4 are the calibration curves which would have been developed if this approach was used.

The second, more complex approach used involved gaining an additional perspective on the calibration results by plotting the slope of the calibration curve as a function of the well water level. This provided a means of visualizing the variation in the calibration curve slopes between each data point and between the calibration "in" and calibration "out" curves for equivalent sections in the storage zone. Theoretically, if the storage zones were geometrically perfect, such a set of graphs would depict straight horizontal lines with a horizontal value equal to the slope of the calibration curve. Such was not the case with the measured data for any of the lysimeters although the slopes of the various lysimeters were reasonably similar in value.

The next step in this approach involved performing a regression analysis to detect trends in the calibration curve slopes for both the calibration "in" data and the calibration "out" curve for all the lysimeters calibrated. Based on the assumption that it took equal periods of time for the lysimeters to equilibrate when water was being pumped in as it did during the pump out procedure, an average slope for each interval was determined by taking the regression line developed for the calibration "in" and the regression line developed for the calibration "out". The line segments possessing the average slope were then plotted to form the single calibration curves which are presented in Figures 2.4 to 2.7. Note that in order to simplify conversion of water storage levels into a percent of total precipitation, the water volumes in these figures have been converted to a depth of water in millimetres over the lysimeter's constant 9.3 square metre surface area. As with the other approach to calibration curve development, no abrupt change in slope on either extreme of the curve is apparent due to the fact that the slow recharge rate of the bordering sand layers did not facilitate collection of reliable well water level data in these zones. There is no specific reason for selecting for presentation in Figures 2.4 to 2.7 the set of calibration curves prepared by this second approach ahead of those prepared using the first method, other than the fact that this second method makes full use of all of the calibration data collected. The calibration curves developed from the first method can be found in Appendix B to facilitate comparison of the results generated by the two approaches.

FIGURE 2.4: Calibration Curve for Lysimeter #1



(NOTE: VOLUME EXPRESSED AS DEPTH OF WATER OVER THE LYSIMETER'S SURFACE AREA)

FIGURE 2.5: Calibration Curve for Lysimeter #2

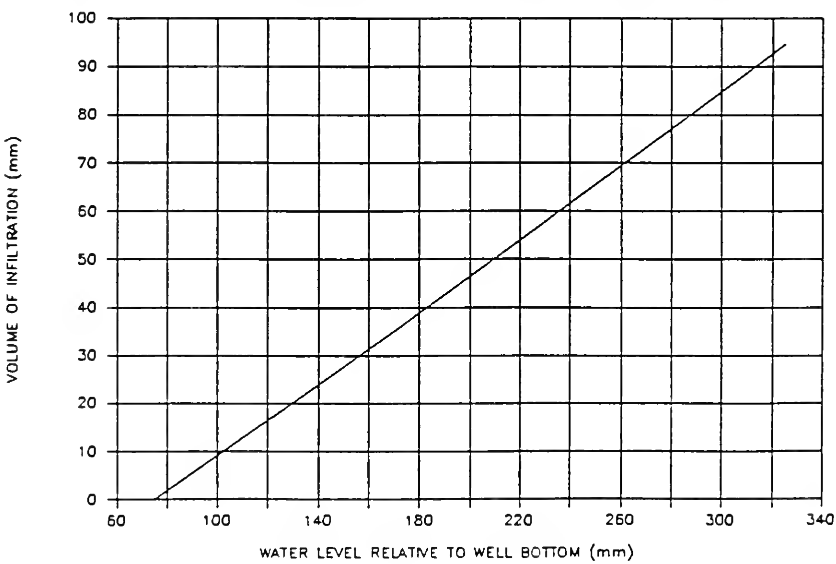
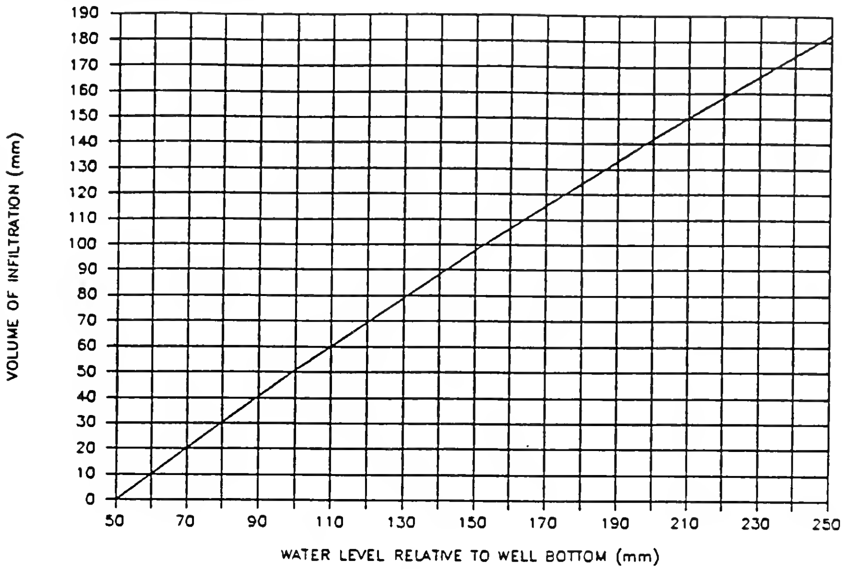
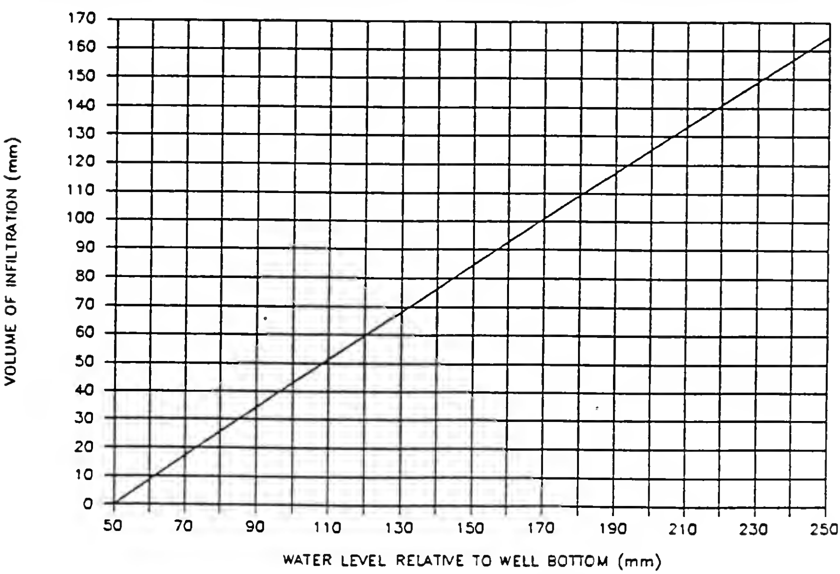


FIGURE 2.6: Calibration Curve for Lysimeter #3



(NOTE: VOLUME EXPRESSED AS DEPTH OF WATER OVER THE LYSIMETER'S SURFACE AREA)

FIGURE 2.7: Calibration Curve for Lysimeter #4



3.0 INFILTRATION STUDY

3.1 Lysimeter Response to Precipitation

The rationale for requiring a minimum equivalent of one calendar year of data was outlined previously in section 1.1. The data presented here was collected between May 1, 1988 and April 31, 1989. A portion of this data was reported previously (Ecologistics Limited, 1989) but is included here for completeness as well as to facilitate a discussion of "seasonal" infiltration rate characteristics.

Figures 3.1 to 3.4 illustrate the portion of precipitation which infiltrated through the Britannia Road landfill cover system and which was captured beneath in the lysimeters' storage zones. Three primary sources must be included when discussing the moisture inputs to the lysimeters. The three sources are rainfall, snowmelt and run-on. Figures 3.1 to 3.4 also present the daily precipitation as it was recorded at the nearby Pearson International Airport.

The data shown on Figures 3.1 to 3.4 is presented to indicate trends only. A more detailed set of hydrographs partitioned into two month periods follow in section 3.3 for analysis and discussion. Due to the presence of up-gradient barriers, Figures 3.1 and 3.3 show data trends collected for infiltration of precipitation in the immediate area of the lysimeters. The trends shown by these hydrographs are very similar once one considers the different porosities of the storage medium employed with lysimeter 1 possessing a gravel storage zone and lysimeter 3 possessing a tile type zone. Figures 3.2 and 3.4 illustrate the data collected for infiltration of precipitation in the immediate vicinity of the lysimeters as well as run-on originating from up the slope due the absence of up-gradient barriers.

The following is a description of the apparent trends illustrated in Figures 3.1 through 3.4. For the May-June period, infiltration leading to through-cover infiltration was concurring at a relatively constant rate. Through the summer months of July, August and September there was very little deep drainage as indicated by relatively horizontal lines on the charts. In the fall, frequent precipitation resulted in increased deep drainage particularly in mid November. Through the winter months of December to March very little through-cover infiltration was collected. The April thaw resulted in immediate and significant responses from all lysimeters, most obviously from numbers 2 and 4 which filled their storage zones in a matter of days With these general trends noted, a more detailed event response analysis was undertaken as described in section 3.3.

Figure 3.1: Lysimeter #1 Well Hydrograph
and Precipitation Data

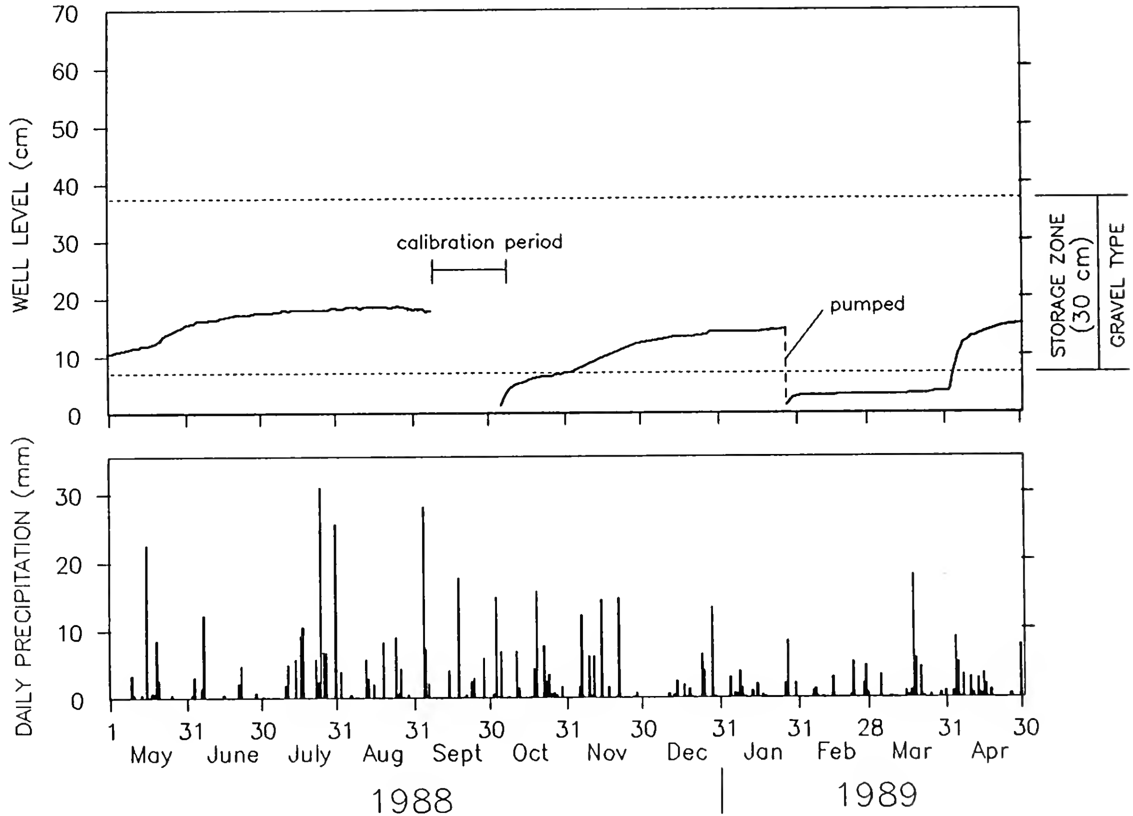


Figure 3.2: Lysimeter #2 Well Hydrograph and Precipitation Data

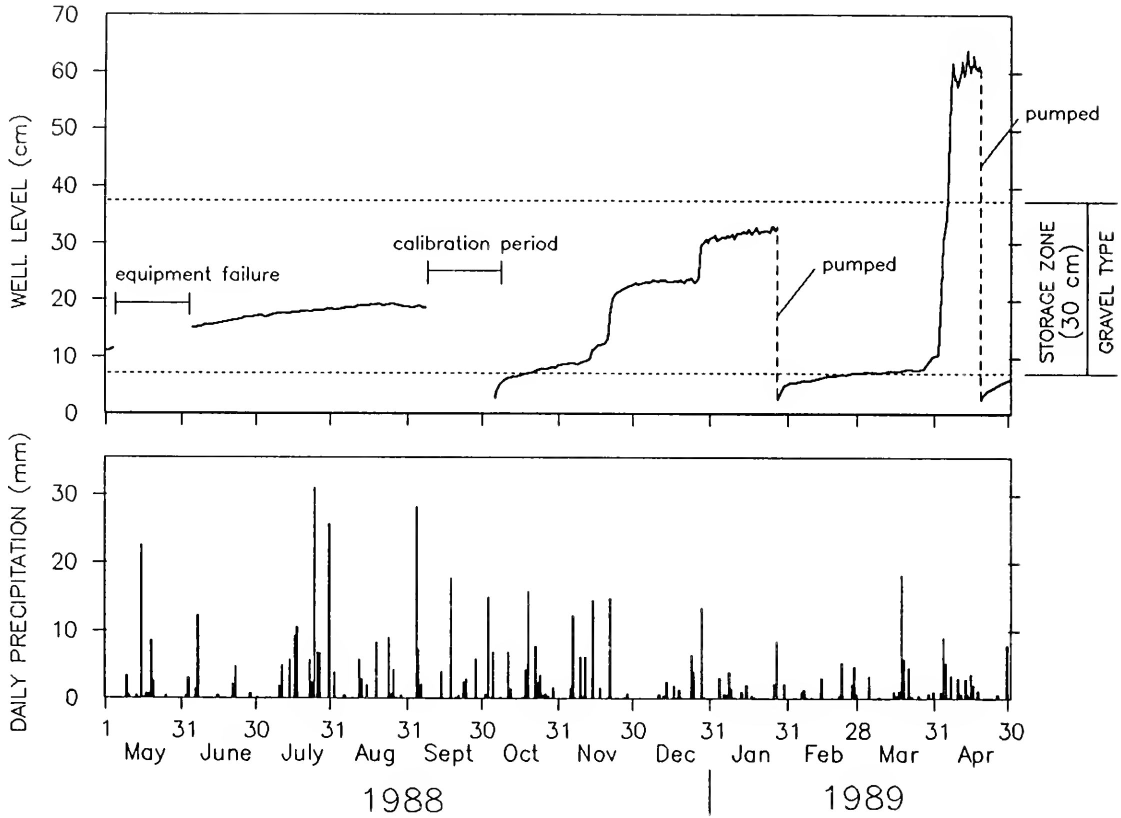


Figure 3.3: Lysimeter #3 Well Hydrograph and Precipitation Data

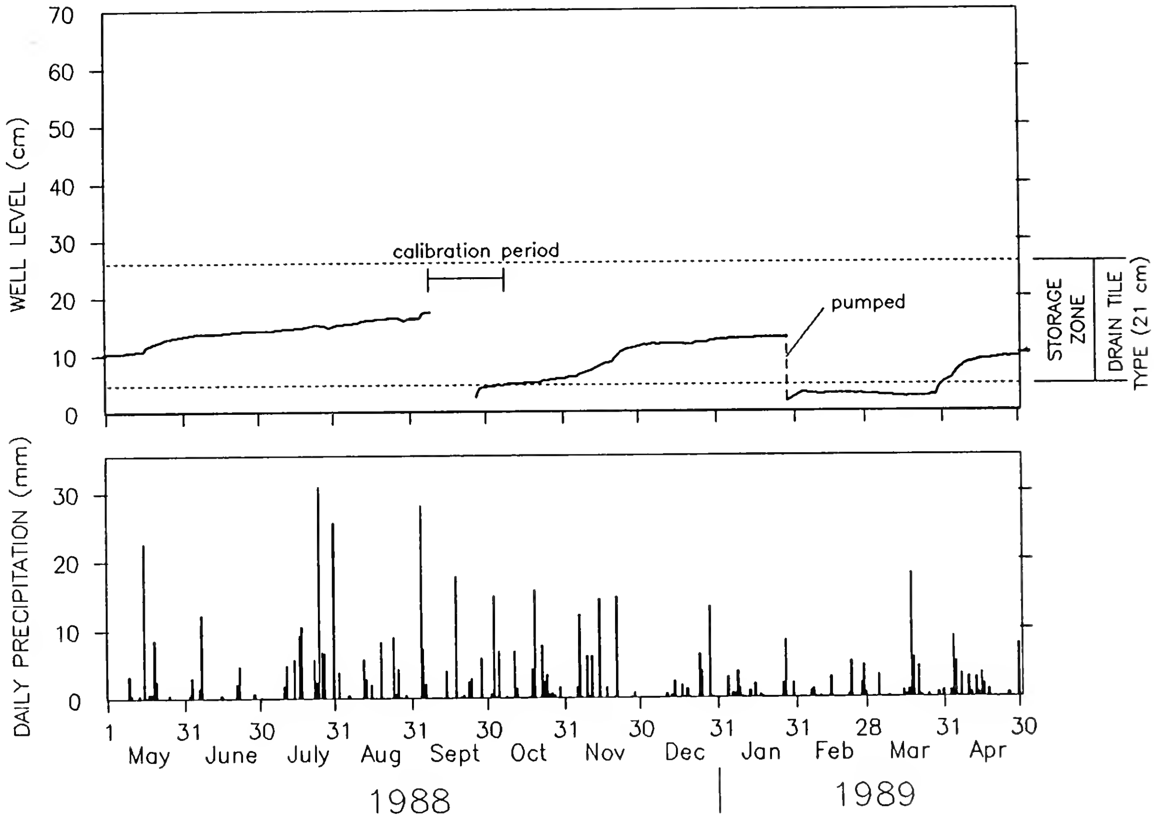
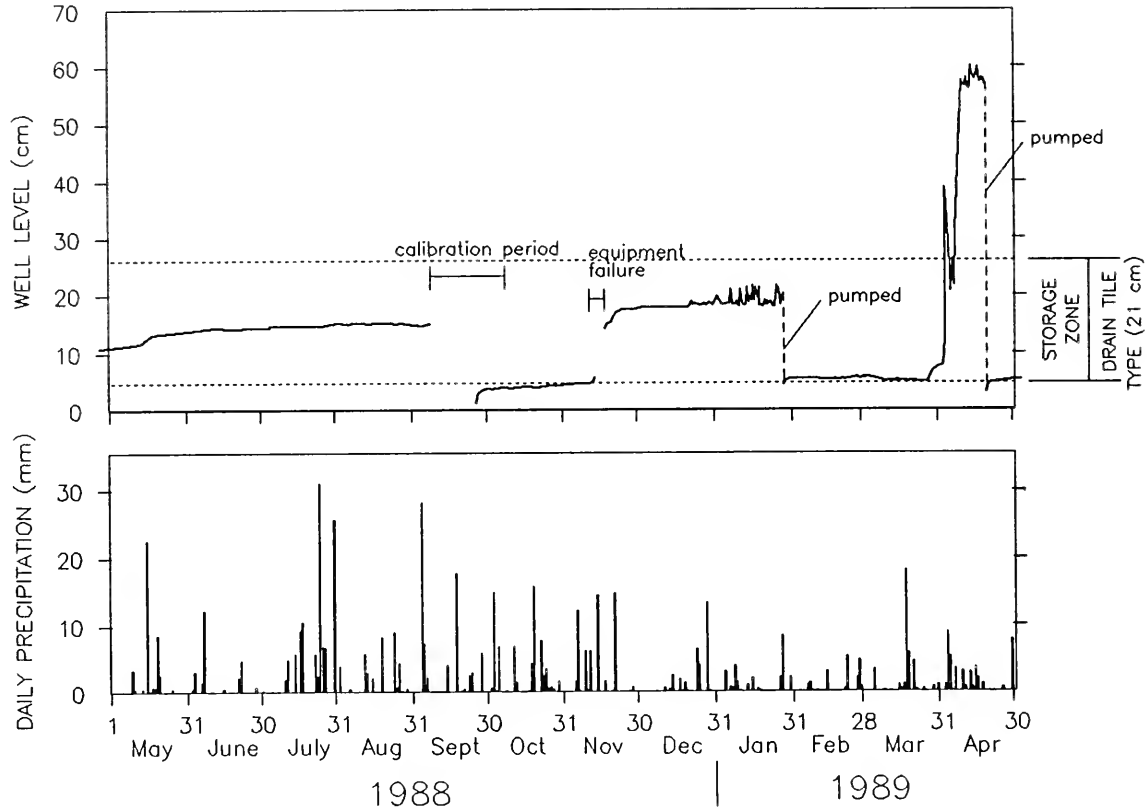


Figure 3.4: Lysimeter #4 Well Hydrograph and Precipitation Data



3.2 Lysimeter Features

Prior to analyzing the lysimeter response curves in detail it may be worth noting the different features among lysimeters which evolved upon the outset and during the course of this study.
As outlined previously in section 2.0 the lysimeter storage zone mediums were constructed of two different materials. In addition, gas transfer tubes, while specified for all lysimeters, were only installed on lysimeters 2 and 3. These differences as well as other variable factors which were initiated or arose during the monitoring period are summarized in Table 3.1 for use as a quick reference. The subsections which follow outline the reasons for the lysimeter being altered or having to be altered.

TABLE 3.1
MATRIX OF LYSIMETER FEATURES

FEATURE	1	2	3	4
Tile Storage Medium			*	*
Gravel Storage Medium	*	*		
Barriers	*		*	
Gas Transfer Tubes		*	*	
Surface Vents			*	*
Surface Depressions (cm)	7	10	10	4
Lysimeter Settlement (cm)	8	7	6	9

3.2.1 Barriers

In 1988 it was speculated that the lysimeters had settled into the landfill cover more than had been anticipated during the design and construction phases. It was further speculated that this settlement had resulted in "dishes" or "bowls" being formed above the lysimeter area leading to increased infiltration as both surface and subsurface run-on collected in these depressions rather than continuing to flow downslope as run-off. On May 5, 1988, galvanized metal barriers were installed up-gradient from lysimeters 1 and 3 to test the "bowl" hypothesis in order to obtain data of deep drainage which was representative of the more uniform areas of the cover where no puddles existed -- the predominant condition which exists on the landfill.

3.2.2 Gas Transfer Tubes

The original lysimeter design called for gas transfer tubes on all lysimeters to ensure gas pressures both inside and outside the lysimeter were equal. At the time of installation this plan was amended and only lysimeters 2 and 3 were constructed with the transfer tubes. Two designs were employed at the time of installation. Later, when the well casings were drilled to facilitate an efficient gas exchange in order to eliminate atmospheric pressure influences, the possibility was removed of evaluating the influence, if any,

positive gas pressure generated by the landfill itself has on percolation through the cap. Based on the strong odour emitted when the recorder hoods are raised, it can be safely surmised that gases are migrating into the lysimeters and escaping through the stage recorder well. All lysimeters are similar then in that they have all been successfully vented. Venting the storage zone through the well casing, as described previously, was necessary if infiltration was to be monitored using a well open to the atmosphere in combination with a water level recorder, both of which are characteristic components of the given lysimeter design.

3.2.3 Surface Vents

When investigating the concept that barometric pressure was affecting water levels in the well (for details refer to Ecologistics Limited, 1989), one or two surface vents were installed in lysimeters 3 and 4 by drilling a hold through the clay cap to the lysimeter's storage zone. In some instances an ABS pipe was installed. In other cases, the vent holes drilled during the investigation were back-filled. Either way, these holes could quite conceivably provide a direct pathway for surface and subsurface water to reach the storage zone, which is not available in lysimeters 1 and 2.

3.2.4 Surface Depressions

Surface depressions (bowls) were observed in the summer of 1988. Fill was imported and spread over the lysimeter area to fill the depressions in the fall of 1988 and again in the spring of 1989. As discussed in 3.2.2 the bowls were undesirable as they caused unrepresentative infiltration. Figure 3.5 illustrates the extent of fill required to bring the landfill cover back to grade over each of the lysimeters. Lysimeters 1, 2, 3 and 4 required 7, 10, 10 and 4 centimetres of fill, respectively.

3.2.5 Lysimeter Settlement

In 1988 each of the lysimeters were surveyed to a permanent benchmark. In the spring of 1989 the survey was repeated to determine the extent of lysimeter settlement. As shown in Table 3.2, the settlement of lysimeters 1, 2, 3 and 4 was 8, 7, 6 and 9 cm, respectively. This settlement could be the result of one or a combination of the following:

1. The entire shelf on which the lysimeters are installed settled due to decomposition of the refuse below.
2. The lysimeter unit itself settled into the hole which was excavated for installation purposes.
3. The base of the lysimeter bulged downward allowing the flagstone (i.e. the survey reference point) to settle.

FIGURE 3.5: Landfill Cover Profile in Vicinity of Lysimeters

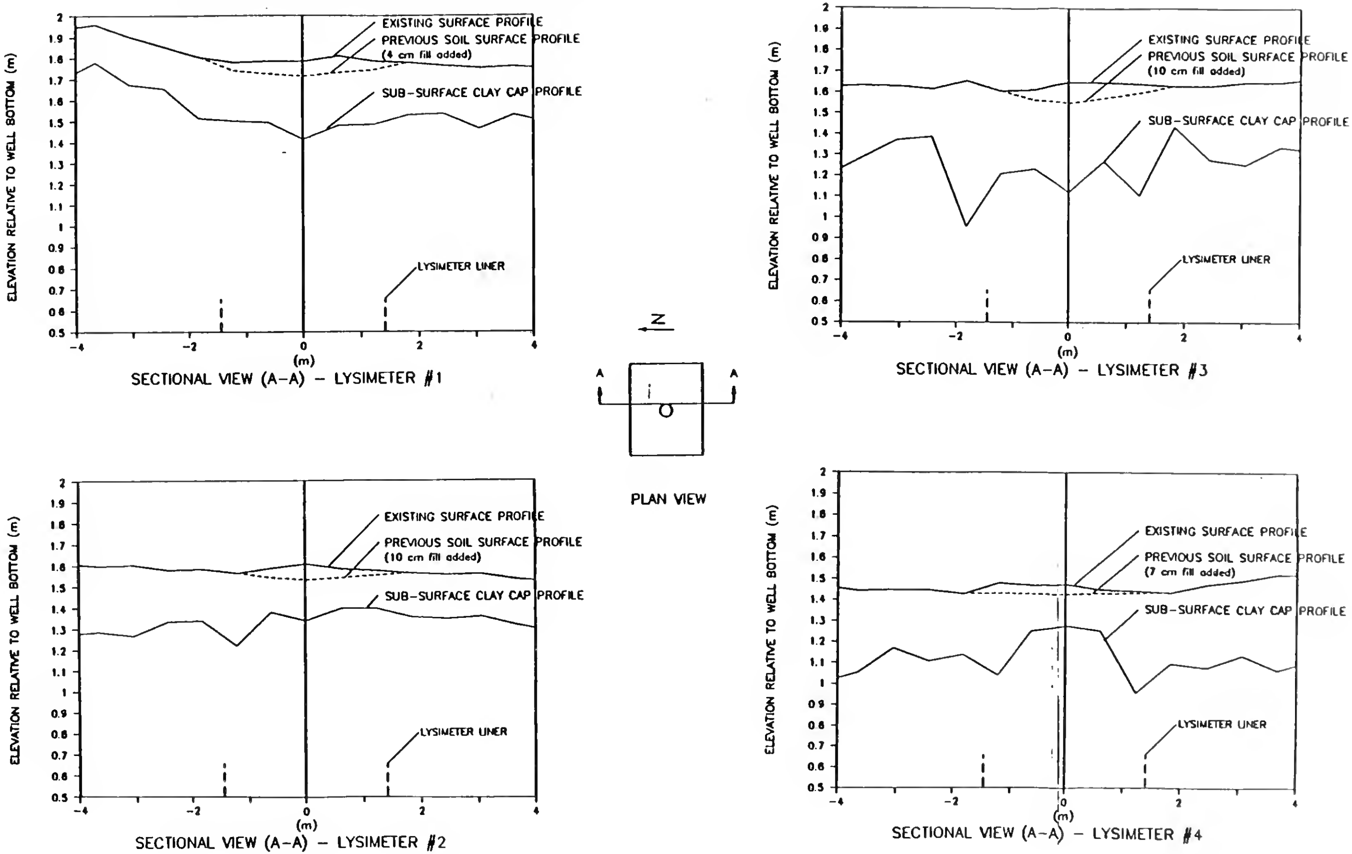


TABLE 3.2

QUANTITATIVE SUMMARY OF LYSIMETER RESPONSES

LYSIMETER #1

PERIOD	CUMULATIVE MONTHLY PRECIPITATION		WELL WATER DEPTH (mm)	VOLUME STORED[1] (mm)	COMMENTS
May - June 1988	64.6	Li	104	9	
		Lf	177	36	
		Net	73	27	
		% OF TOTAL PRECIPITATION		41.8%	
July - Aug. 1988	146.9	Li	177	35	
		Lf	184	38	
		Net	7	3	
		% OF TOTAL PRECIPITATION		2.0%	
Sept. - Oct. 1988	138.2	Li	184	38	- break for calibration
		Lf	184	38	
		Net	0	0	
		Li2	40	N/A	- assumed 25% porosity in sand zone
		Lf2	72	N/A	
		Net	32	8	
		Total Net	32	8	
		% OF TOTAL PRECIPITATION		5.8%	
Nov. - Dec. 1988	88.8	Li	72	N/A	- assumed 25% porosity in sand zone
		Lf	75	N/A	
		Net	3	0.75	
		Li2	75	0	
		Lf2	144	24	
		Net	69	24	
		Total Net	72	24.75	
		% OF TOTAL PRECIPITATION		27.9%	
Jan. - Feb. 1989	44.9	Li	144	24	- pumped out
		Lf	149	26	
		Net	5	2	
		Li2	29	N/A	- assumed 25% porosity in sand zone
		Lf2	34	N/A	
		Net	5	1.25	
		Total Net	10	3.25	
		% OF TOTAL PRECIPITATION		7.2%	
Mar. - Apr. 1989	77.9	Li	34	N/A	- assumed 25% porosity in sand zone
		Lf	75	N/A	
		Net	41	10.25	
		Li2	75	0	
		Lf2	156	28	
		Net	81	28	
		Total Net	122	38.25	
		% OF TOTAL PRECIPITATION		49.1%	

LYSIMETER #2

PERIOD		WELL WATER DEPTH (mm)	VOLUME STORED[1] (mm)	COMMENTS
May - June 1988	Li	108	13	
	Lf	170	35	
	Net	62	22	
	% OF TOTAL PRECIPITATION		34.1%	
July - Aug. 1988	Li	170	35	
	Lf	186	42	
	Net	16	7	
	% OF TOTAL PRECIPITATION		4.8%	
Sept. - Oct. 1988	Li	186	42	
	Lf	186	42	
	Net	0	0	
	Li2	55	N/A	- assumed 25% porosity in sand zone
	Lf2	75	N/A	
	Net	20	5	
	Li3	75	0	
	Lf3	84	3	
	Net	9	3	
	Total Net	29	8	
	% OF TOTAL PRECIPITATION		5.8%	
Nov. - Dec. 1988	Li	84	3	
	Lf	303	86	
	Net	219	83	
	Total Net	219	83	
	% OF TOTAL PRECIPITATION		93.5%	
Jan. - Feb. 1989	Li	303	86	- pumped out
	Lf	326	95	
	Net	23	9	
	Li2	49	N/A	- assumed 25% porosity in sand zone
	Lf2	72	N/A	
	Net	23	5.75	
	Total Net	46	14.75	
	% OF TOTAL PRECIPITATION		32.6%	
Mar. - Apr. 1989	Li	72	N/A	- assumed 25% porosity in sand zone
	Lf	75	N/A	
	Net	3	0.75	
	Li2	75	0	
	Lf2	375	99	- pumped out 1040 litres
	Net	300	99	
	Li3	40	N/A	- assumed 25% porosity in sand zone
	Lf3	58	N/A	
	Net	18	4.5	
	Total Net	321	104.5	
	% OF TOTAL PRECIPITATION		134.0%	

LYSIMETER #3

PERIOD		WELL WATER DEPTH (mm)	VOLUME STORED[1] (mm)	COMMENTS
May - June 1988	Li	103	54	
	Lf	144	93	
	Net	41	39	
	% OF TOTAL PRECIPITATION		60.4%	
July - Aug. 1988	Li	144	93	
	Lf	164	111	
	Net	20	18	
	% OF TOTAL PRECIPITATION		12.3%	
Sept. - Oct. 1988	Li	164	111	
	Lf	175	120	
	Net	11	9	
	Li2	45	N/A	- assumed 25% porosity in sand zone
	Lf2	50	N/A	
	Net	5	1.25	
	Li3	50	0	
	Lf3	61	12	
	Net	11	12	
	Total Net	27	22.25	
	% OF TOTAL PRECIPITATION		16.1%	
Nov. - Dec. 1988	Li	61	12	
	Lf	127	77	
	Net	66	65	
	Total Net	66	65	
	% OF TOTAL PRECIPITATION		73.2%	
Jan. - Feb. 1989	Li	127	77	- pumped out
	Lf	131	80	
	Net	4	3	
	Li2	30	N/A	- assumed 25% porosity in sand zone
	Lf2	31	N/A	
	Net	1	0.25	
	Total Net	5	3.25	
	% OF TOTAL PRECIPITATION		7.2%	
Mar. - Apr. 1989	Li	31	N/A	- assumed 25% porosity in sand zone
	Lf	50	N/A	
	Net	19	4.75	
	Li2	50	0	
	Lf2	97	47	
	Net	47	47	
	Total Net	66	51.75	
	% OF TOTAL PRECIPITATION		66.4%	

LYSIMETER #4

PERIOD		WELL WATER DEPTH (mm)	VOLUME STORED[1] (mm)	COMMENTS
May - June 1988	Li	110	52	
	Lf	144	80	
	Net	34	28	
	% OF TOTAL PRECIPITATION		43.3%	
July - Aug. 1988	Li	144	80	
	Lf	149	85	
	Net	5	5	
	% OF TOTAL PRECIPITATION		3.4%	
Sept. - Oct. 1988	Li	149	85	
	Lf	150	86	
	Net	1	1	
	Li2	39	N/A	- assumed 25% porosity in sand zone
	Lf2	44	N/A	
	Net	5	1.25	
	Total Net	6	2.25	
	% OF TOTAL PRECIPITATION		1.6%	
Nov. - Dec. 1988	Li	44	N/A	- assumed 25% porosity in sand zone
	Lf	50	N/A	
	Net	6	1.5	
	Li2	50	0	
	Lf2	186	115	
	Net	136	115	
	Total Net	142	116.5	
	% OF TOTAL PRECIPITATION		131.2%	
Jan. - Feb. 1989	Li	186	115	- pumped out
	Lf	203	127	
	Net	17	12	
	Li2	56	5	
	Lf2	56	5	
	Net	0	0	
	Total Net	17	12	
	% OF TOTAL PRECIPITATION		26.7%	
Mar. - Apr. 1989	Li	56	5	- pumped out 1150 litres
	Lf	260	169	
	Net	204	164	
	Li2	49	N/A	- assumed 25% porosity in sand zone
	Lf2	50	N/A	
	Net	1	0.25	
	Li3	50	0	
	Lf3	53	3	
	Net	3	3	
	Total Net	208	167.25	
	% OF TOTAL PRECIPITATION		215.0%	

LEGEND:

Li - initial well level; Lf - final well level; Net - final minus initial well level; Li2, Lf2 - indicates initial and final levels of a second line segment following a break in well level data; N/A - not applicable

NOTE:

1. Lysimeter storage volumes are expressed as depth of water over the Lysimeter's 9.3 m^2 surface area
2. To ensure well level had reached static conditions, well level readings used in calculations were taken three days following pump out

3.3 Detailed Analysis

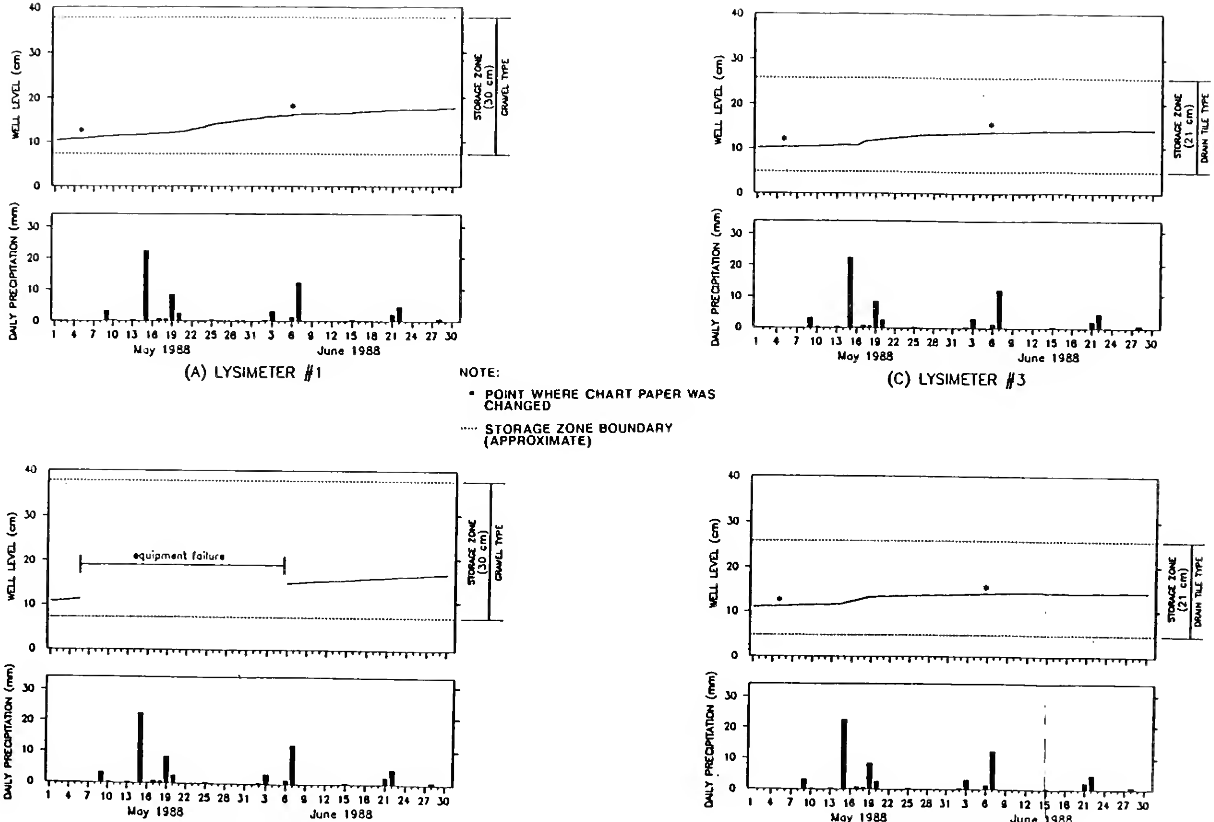
With the general objective of this study being to evaluate and test the lysimeters' ability to accurately measure the through-cover infiltration of a landfill cap and thus quantify not only annual infiltration volumes, but also to measure, if possible, the infiltration rates associated with seasonal and even individual precipitation events, a detailed analysis of observations was needed. To accommodate such an analysis the hydrograph-extracted data, which is available in full on a 5 1/4" floppy diskette in Appendix C, was partitioned into six (6) - two (2) month periods. A graphical presentation of this period of data is shown in Figures 3.6 through 3.11 along with Pearson International Airport precipitation data for the same period. To further aid in hydrograph analysis, Table 3.2 was prepared to numerically summarize initial and final water levels shown on the two-month graphs as well as to indicate the percentage of precipitation these changes in storage represent. All four lysimeter hydrographs for the same time period were placed on a single page for ease of comparison of results among lysimeters.

3.3.1 May-June 1988

As is evident from Figure 3.6, each of the four lysimeters responded in a relatively similar manner to the 64.6 millimetres of precipitation which fell during this period. A visual observation made at the time the barriers were installed in May revealed that there was a considerable depression or "bowl" over lysimeter 3. Thus, this depression could have been collecting and temporarily storing the run-off generated by the precipitation from an area greater than the 9.3 m^2 on which the lysimeter well is centred. Moreover, as indicated by the cross-section on Figure 3.5 c, the local area surrounding the lysimeter from this view would appear to slope towards the lysimeter area, meaning that this larger area could also contribute to greater through-cover infiltration than is representative of the lysimeter area.

With respect to individual event responses, it was only following the May 15 rain that any increase in the rate of infiltration could be noted. Lysimeters 1 and 4 responded steadily and relatively similarly indicating similar moisture contents in the soil profile at the time of the precipitation event. This is consistent with the total deep drainage collected from 1 and 4 which were 41.8 and 43.3 percent of precipitation respectively. Lysimeter 2 also responded similarly for the period (i.e. 34.1 percent) but due to an equipment failure it is unknown precisely how and when this lysimeter responded. The response curve for lysimeter 3 would seem to indicate that the moisture content of the soil was higher than for the others and this facilitated a more immediate response. Alternatively, a preferential flow path could have been present, such as one created by the surface venting procedure the previous fall, which facilitated a rapid response.

FIGURE 3.6: Lysimeter Hydrographs and Precipitation Data (May - June, 1988)



(A) LYSIMETER #1

(B) LYSIMETER #2

(C) LYSIMETER #3

(D) LYSIMETER #4

NOTE:

- • POINT WHERE CHART PAPER WAS CHANGED
- ····· STORAGE ZONE BOUNDARY (APPROXIMATE)

3.3.2 July - August 1988

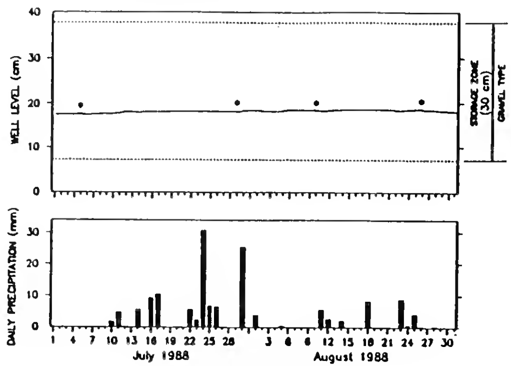
The first three weeks of July 1988 were extremely hot and dry in southern Ontario. Some people refer to this period as the "drought" of 1988. Accordant with this, the response curves (Figure 3.7) are almost horizontal as would be expected. Once again the exception to the general trend is Lysimeter 3 where drainage continued very slowly in the first half of the period and again following the rainfalls of July 22 to 26. A likely explanation for this is a carryover of moisture from the previous period and the continued presence of preferential flow paths. With the grass not fully established in the early summer of 1988, root penetration would not yet be deep enough to remove water from the deeper soil zones. Lysimeter 1 showed a slight drop in water level (i.e. 0.5 cm). Given that later inputs show that leaks did not exist in the lysimeter liner, alternative explanations for this slight decline are needed. One possibility is that the flexible bottom of the lysimeter dropped slightly due to settlement underneath the lysimeter while the well remained stationary. Alternatively, and quite probably, the water level drop could simply be attributed to measurement error inherent with the use of the water level recorders. While being out 0.5 centimetres (0.2 inches) is not normally a major concern with most traditional applications of a water level recorder, being out 0.5 centimetres in this application is significant.

The only other point worthy of comment for this period is the ever so subtle waves or "dips" in the hydrographs. Three plausible explanations have been identified for this phenomenon. One explanation is that it is "noise" created by the looseness or slippage encountered using the Steven's stage recorders which, due to the nature of the mechanical linkage, can move vertically up to 1 centimetre without moving the float. Again, while normally not a significant problem on most chart recorder applications, it is significant when measurements are being made to the nearest millimetre. The second possibility is that it has been speculated that pumping leachate from the leachate collection system each night may be having a modest effect on positive gas pressures which in turn are effecting the water level in the lysimeters. Finally, a third possible explanation for these fluctuations is changing daily temperatures in the soil matrix somehow affecting the water level in the well. An analysis of two hydrographs for a 14 day period revealed that the waves correlate directly with 24 hour periods suggesting a cyclic daily phenomenon. The extent source of this cyclic phenomenon, however, has still not been pin-pointed.

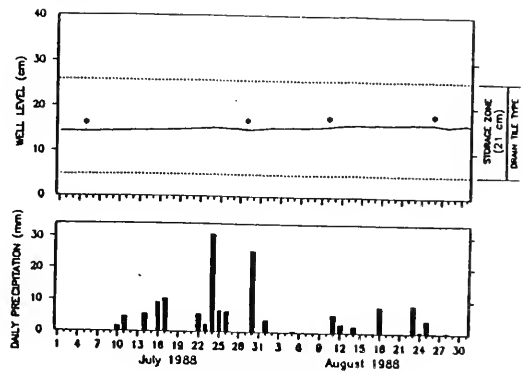
3.3.3 September - October 1988

Figure 3.8 illustrates the response curves preceding and subsequent to the calibration period. Lysimeters 1 and 2 show a trend downwards indicating a slight loss from the storage zone. As with the loss associated with Lysimeter 1 in the July - August period however, measurement error or bottom bulging of the storage lines is suspected to be the cause for the slight drop. Actual in-field water level measurements taken each time the charts were changed indicated no change in water level occurred between chart changes and therefore a slight mechanical measurement error is suspected. Once again, Lysimeter 3 recorded more response than any other lysimeter. Expressing the graphs in numerical

FIGURE 3.7: Lysimeter Hydrographs and Precipitation Data (July - August, 1988)



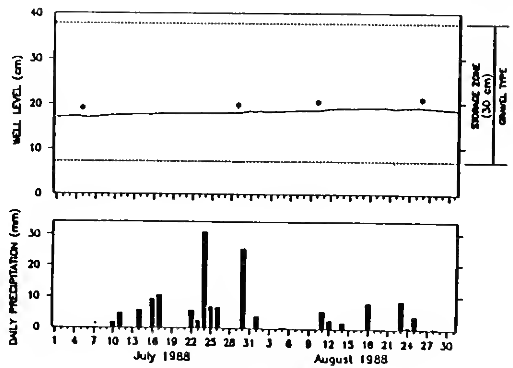
(A) LYSIMETER #1



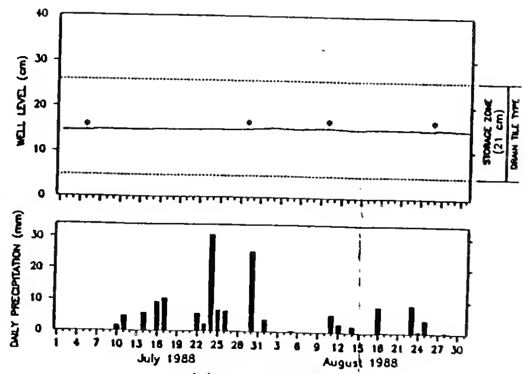
(C) LYSIMETER #3

NOTE:

- • POINT WHERE CHART PAPER WAS CHANGED
- ..... STORAGE ZONE BOUNDARY (APPROXIMATE)

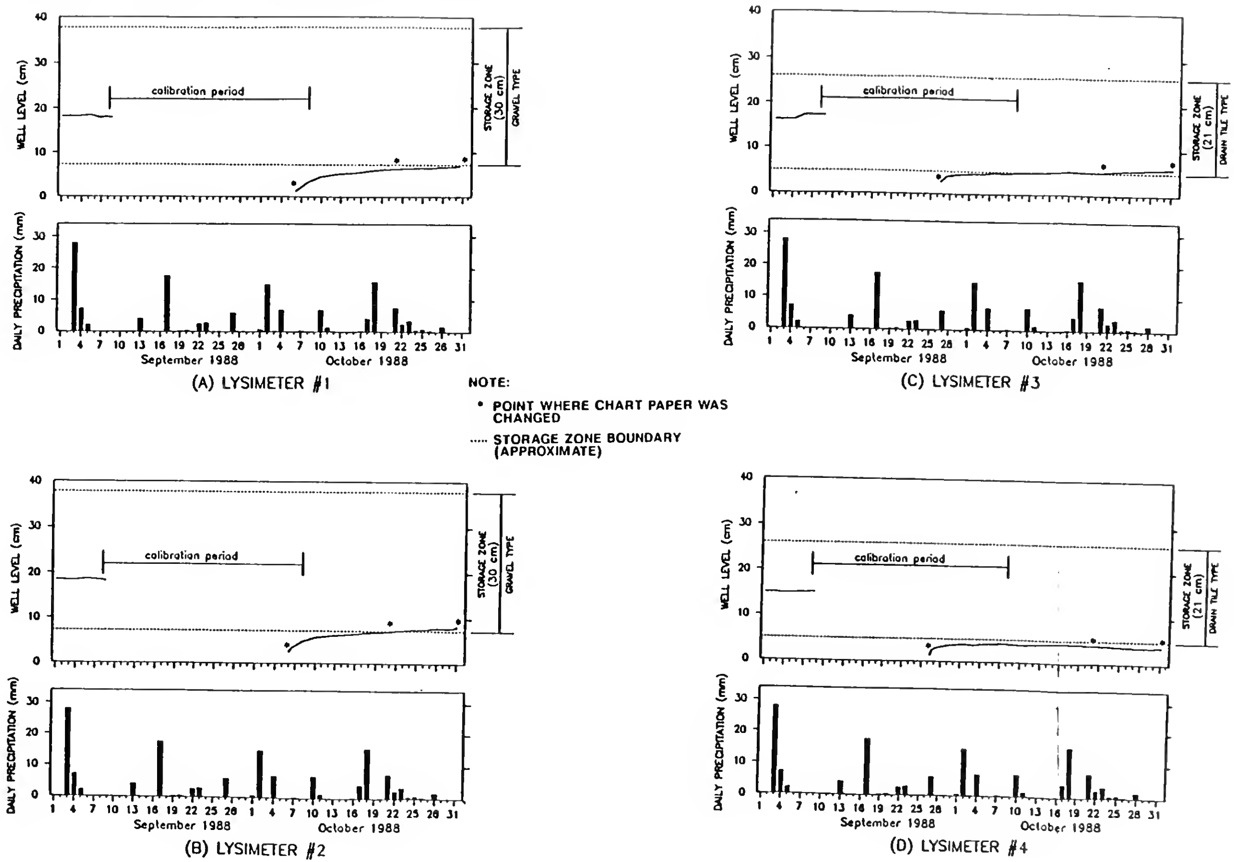


(B) LYSIMETER #2



(D) LYSIMETER #4

FIGURE 3.8: Lysimeter Hydrographs and Precipitation Data (September - October, 1988)



terms, of the 138 millimetres of precipitation which fell during the period, 16.1 percent is reported to have been captured as through-cover infiltration in lysimeter 3. This compares with 5.8, 5.8 and 1.4 percent for Lysimeters 1, 2 and 4 respectively. The 16.1 percent is the equivalent of 22.3 millimetres or 2.23 centimetres in a system which inherently can record error of up to 1.0 centimetre. This data clearly demonstrates the need to incorporate a storage area in the lysimeter design that is a much more sensitive to system inputs. A more sensitive recording apparatus is one possibility although preliminary investigation of this alternative suggests it could be prohibitively expensive to purchase and install such a sensitive measurement tool. The second more economical approach to detect low level input to the storage zone would be to magnify the input response by altering the storage zone itself. At present, due to the characteristic high porosity of the storage mediums used, detecting water level height changes is difficult. For instance, for the tile drain storage zone, an input volume of 100 millimetres of water over the surface area of the lysimeter yields approximately a 120 millimetre change in well level. The gravel medium, while not as porous still yields only a 250 millimetre curve response when 100 millimetres of water is added to the storage zone. A more appropriate and accurate response curve would yield a 600 millimetre to 1000 millimetre rise in well level for each 100 millimetres of input. Achieving such exaggeration is discussed in more detail in section 6.

It should be noted that following calibration, the initial hydrograph water level was located below the "assumed" bottom of the storage zone. As discussed previously, due to inherent design characteristics of the storage zones, it was essentially impossible to calibrate the lysimeters in these regions. The relatively slow and unpredictable recharge characteristics of the storage zone also affected our ability to determine at what point the pumping procedure should cease in order to leave the water level at the bottom yet slightly within the storage zone. Therefore water volumes stored can, at best, be only mathematically approximated on the basis of a typical pore space ratio of 25 percent for the sand that forms this lower region.

Finally, note that following the pump-out at the end of the calibration period, there is a relatively rapid rise in lysimeter well level. One argument for this could be that the datum for the storage zone is incorrect and this more rapid rise can be attributed to the lower porosity in the underlying sand layer. While this is quite possible, given the uncertainty of knowing the exact location of this boundary, in reviewing all four graphs and based on experience gained during the calibration of the lysimeters, it would appear that the rapid rises are more likely to be attributable to the lag time required for water in the storage zone to recharge the well and reach steady state. Note that the graphs for the drain tile type lysimeters show a shorter recharge time (i.e. a steeper slope on well level curve) for the drain tile type lysimeters than do the gravel type lysimeters graphs. This slower recharge rate for the gravel storage zones rather than for the tile storage zones is consistent with observations made during calibration of the lysimeters. If the change in slope was attributable to the location of the storage zone boundary only, then a distinction in curve slope between storage zone types should not have been noticeable, for in both cases, the layer below the storage zone is sand.

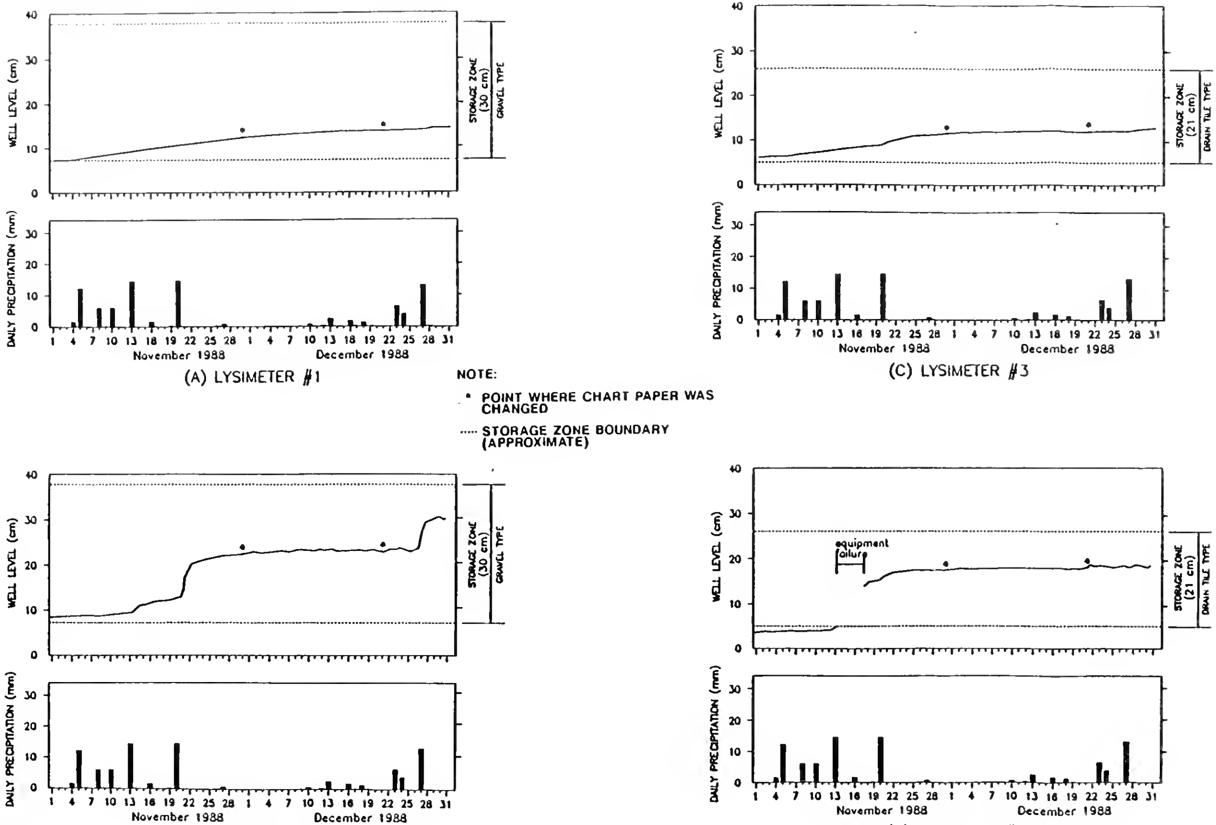
3.3.4 November - December 1988

Whereas the precipitation which fell on the site in September and October was only enough to result in minor through-cover infiltration, apparently it was sufficient to maintain the moisture content in the soil profile at or near field capacity. As a result, when it rained in November, the response was relatively rapid. Lysimeter 1 responded with a steady rise well into December as is illustrated in Figure 3.9 a. Similarly lysimeter 3 (Figure 3.9 c) responded steadily but with more sharply defined steps. This more step-like rise in lysimeter 3, particularly since it follows shortly after a relatively wet period would lead to the conclusion that a supply of water is being collected as through-cover infiltration through a "short-circuit" pathway in the cover's profile over lysimeter 3.

The November - December response curves were the first to clearly demonstrate the effect of barrier installation upslope from lysimeters 1 and 3. The barrier's impact can best be seen in comparing response curves for lysimeters 2 and 4 with those for lysimeters 1 and 3. Unlike lysimeters 1 and 3, where the response curves were gradual, lysimeters 2 and 4 had very rapid responses. Figures 3.9 b and 3.9 d show that precipitation which fell in November on lysimeter 2 and 4 resulted in immediate responses. The responses, however, were not equivalent in magnitude and did not occur within the same period of time. For instance, the precipitation events which occurred in the first three weeks of November yielded a small step-like rise on the hydrograph for lysimeters 2 by November 18 and a second larger rise on November 21. In contrast, for the same period, lysimeter 4 had a large step-like rise by the eighteenth of the month and a subdued response to precipitation on November 21. In addition, lysimeter 2 responded with a large step-up at the end of December, but lysimeters 1, 3 and 4 showed only relatively small responses.

It is evident upon evaluation of the four hydrographs for the November - December period that the through-cover captured in the lysimeter storage zone varies significantly among lysimeters for this period. However, it was only upon analysis of the data that the magnitude of this variability was appreciated. For the two month period, lysimeter 1 captured 27.9 percent of the total precipitation which fell within this period, lysimeter 2 captured 93.5 percent , lysimeter 3 recorded 73 percent while lysimeter 4 gathered an equivalent of 131 percent of the total precipitation. These numbers are in sharp contrast to previous months results when lysimeter 3 was showing the highest proportion of deep drainage. Thus the impact of the up-slope barriers when the soils are at a higher moisture content was made quite clear. The observations, particularly for lysimeter 4, whose infiltration value exceeded the total rainfall input for the period, help confirm that run-off from up-slope areas collected in the lysimeters' clay surface depressions, created through settlement and/or construction traffic, exaggerated the infiltration data that would have normally been collected if only deep drainage from a 9.3 square metre area was being stored.

FIGURE 3.9: Lysimeter Hydrographs and Precipitation Data (November - December, 1988)



(A) LYSIMETER #1

(B) LYSIMETER #2

(C) LYSIMETER #3

(D) LYSIMETER #4

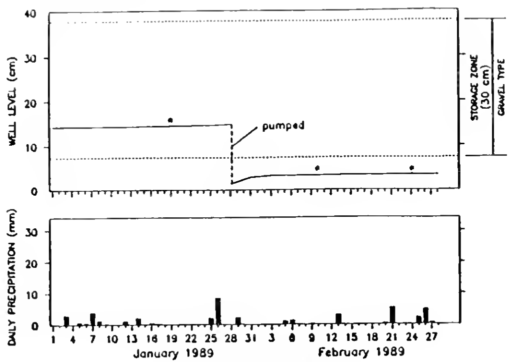
It is the study team's opinion that it is virtually impossible to have instantaneous responses of the magnitude recorded in November and December through clay soils such as those found at the Britannia Road Landfill site without the presence of some form of preferential flow path to the storage zone. Many possible reasons could explain the existence of the preferential pathways. They could be a result of a series of large pores in the soil matrix, vertical cracks resulting from settlement, channels created from the installation of surface vent pipes the year previous or the consequence of freezing soils, including the bentonite seal material, condensing and pulling away from the monitoring well. What the actual path is in the Britannia Road lysimeters is unknown but their presence likely exists, to some degree, in at least three of the four lysimeters. It is interesting to note that, while collecting data necessary for the preparation of the soil profiles presented in Figure 3.5, the landfill cap within lysimeter 3 was found to be not as well compacted as it was around the other lysimeters. This would suggest that the first possibility, larger pores in the soil matrix, could be a likely source of pathway through the soil profile to the storage zone in lysimeter 3. Such a pathway would be more likely to give the more gradual yet higher than normal response seen generated for this period by lysimeter 3.

Cracks or a connecting series of large pore spaces can be present and yet not conduct significant volumes of soil moisture in dry and even relatively wet soils. However, if a continuous source of water is available to act as a supply, such as from up-slope run-off or ponding on the surface, the crack can then act as a conduit and water can be transferred by gravity flow through a soil profile in minutes. It is this process which has likely taken place in lysimeters 2 and 4 during November and December. Precipitation that fell on the lysimeters is suspected to have been augmented by subsurface run-off which originated up-slope from the lysimeters and traversed along the clay-loam interface. Depressions in the clay cap acted as reservoirs which, as they filled, induced positive downward pressures thereby accelerating infiltration and causing large recorder responses as the storage zones rapidly filled.

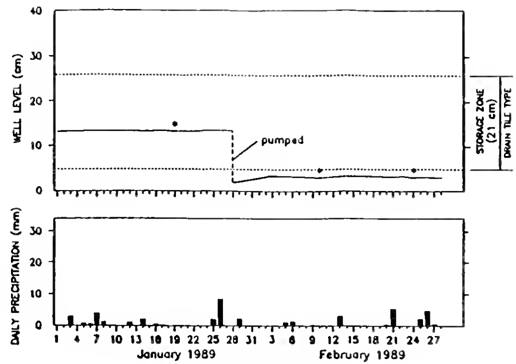
3.3.5 January - February 1989

The response curves for this period are very revealing with respect to two features of the existing lysimeter installations. First, Figures 3.10 a and 3.10 c representing lysimeters 1 and 3 are nearly identical to one another for this period in terms of shape. Quantitatively, they are identical, with both response curves representing the equivalent of 7.2 percent of the recorded precipitation. In contrast lysimeters 2 and 4 (Figures 3.10 b and 3.3.5 b) measured the equivalent of 32.6 and 26.7 percent of recorded precipitation. It is not thought to be a coincidence that the two lysimeters with barriers measured identical and relatively small amounts of through-cover infiltration compared to the two lysimeters without barriers. Clearly the barricades are acting as intended by deflecting subsurface flow that originates up-slope away from the lysimeter surface area. Therefore, the data presented for lysimeters 1 and 3 should be seen as being more representative of most of the Britannia Road landfill cover system on similar slopes.

FIGURE 3.10: Lysimeter Hydrographs and Precipitation Data (January - February, 1989)

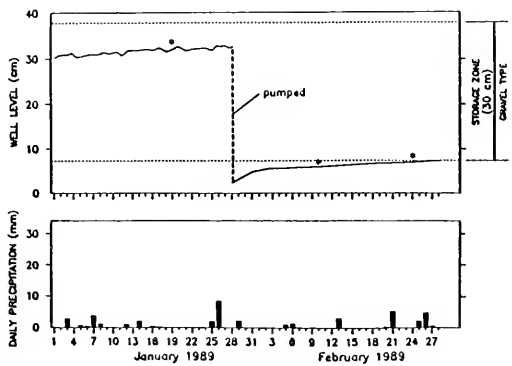


(A) LYSIMETER #1

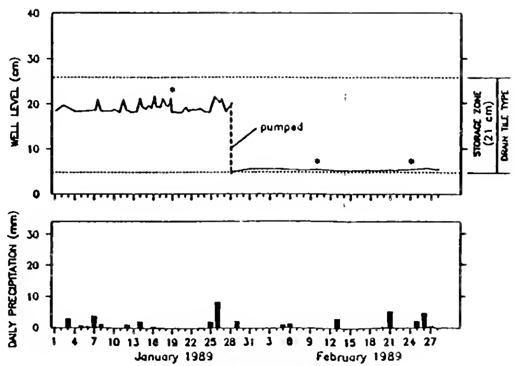


(C) LYSIMETER #3

NOTE:
- • POINT WHERE CHART PAPER WAS CHANGED
- ····· STORAGE ZONE BOUNDARY (APPROXIMATE)



(B) LYSIMETER #2



(D) LYSIMETER #4

While steel barriers proved to be effective as a post-construction means of controlling subsurface run-on, an even more suitable approach may have been to extend the lysimeter storage liners to or as near as possible to the landfill surface. Original notes on the Britannia lysimeter design proposed that the liners be extended to the surface. If this concept had been carried through to construction, additions to the storage zone attributable to subsurface lateral flow would have been eliminated. It is recognized that subsurface lateral flow can potentially be a significant moisture source and ideally should not be eliminated from the poritlon of the landfill cap located above the lysimeter. Thls aspect, however, does raise a number of questions. One question is: What proportion of the through-cover infiltration actually originates from subsurface lateral flow? A second asks if the presence of the lysimeter, due to the nature of its installation resulting in different soil densities is having an effect on the normal movement of pathways taken by subsurface water. At present, there is no experimental control and no means of partitioning the inputs with respect to their origin, to assist in answering these questions.

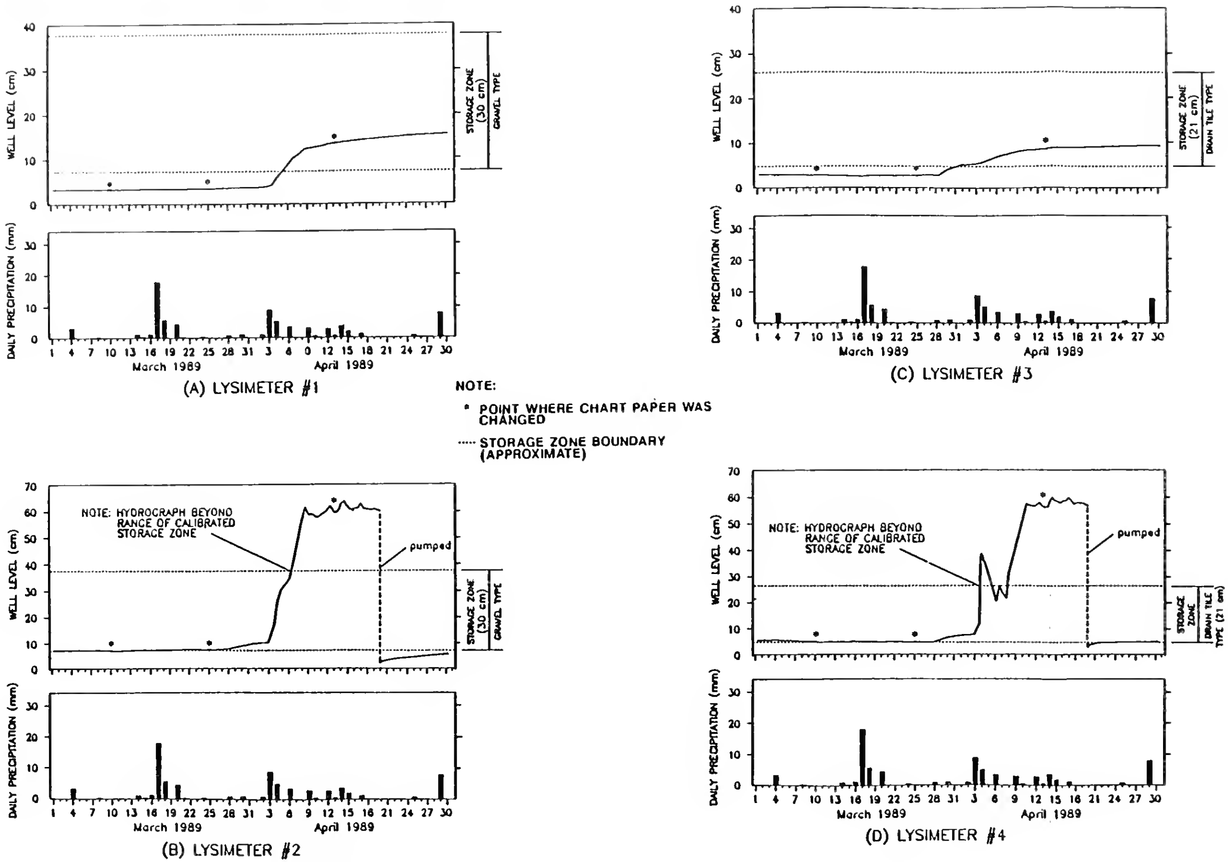
In order to determine if there was sufficient replication of similar systems on which a statistical analysis could be conducted, a randomized block analysis was undertaken. While a more detailed account of this analysis can be found in Appendix D the conclusion was that the four lysimeters as a group differed too significantly to be analyzed in such a manner.

Another aspect worth noting upon detailed inspection of curves for this period is the well level fluctuation or waviness of the well level line once the level approached the upper portions of the storage zone. This trend in well level response began in December for lysimeter 2 and became more and more evident as January passed. Similar fluctuations were seen on lysimeter 4 data. This phenomenon is a consequence of the previously reported barometric effect (Ecologistics Limited, 1989). With the lysimeter storage zone gradually being filled, fewer holes exist to provide the efficient gas exchange needed to eliminate this problem. Note that once the storage wells were pumped out, the problem disappeared. Another yet similar justification for the fluctuation in the well level curve is the possibility that the venting (i.e. drilling) was not sufficient in the upper reaches of the storage zone. A third reason could be that the upper reaches of the storage zone or the storage zone itself is not completely level and a trapped air "bubble" is still influencing recorded data. A combination of any of these is also possible. In the case of lysimeter 4, it is now thought that the last effective vent-hole is located approximately 7 centimetres below the top of the storage zone. When the stored deep drainage exceeded this level, erratic fluctuations were recorded. March - April data provides similar observations to further justify this conclusion.

3.3.6 March - April 1989

At the outset it should be noted that the y-axis scale has been changed from 40 centimetres to 70 centimetres for Figures 3.11 b and 3.11 d. This change was necessary to facilitate presentation of the response curves in their entirety for this period.

FIGURE 3.11: Lysimeter Hydrographs and Precipitation Data (March - April, 1989)



(A) LYSIMETER #1
(B) LYSIMETER #2
(C) LYSIMETER #3
(D) LYSIMETER #4

NOTE: Y-AXIS SCALE CHANGED FOR LYSIMETERS 2 AND 4 TO ACCOMMODATE HYDROGRAPH DATA

Three factors are prominent in Figure 3.11. First is the low level of infiltration during the first four weeks of March. Second is the relative timing of the infiltration response while third is the magnitude of the responses when they were recorded. The lack of infiltration through the month of March can be attributed somewhat to the lack of precipitation but more significantly it can be accounted for in the fact that the landfill cover remained frozen through this period. It was not until March 24 through to the end of the first week of April that mean daily temperatures remained above the freezing point (see Appendix E). This warming trend in the latter part of March resulted in similar responses initially from three of the four lysimeters as the landfill cap thawed. In fact, the response of these three lysimeters appeared to be within hours of each other. The exception was lysimeter 1 where perhaps the known presence of denser vegetation over this lysimeter insulated the ground thereby slowing the soil thawing process and delaying the response until April 3.

The magnitude of the responses as well as the rate of response are very revealing in this period. If preferential flow paths did not exist, it is extremely unlikely that the volume of through-cover infiltration recorded would be present, particularly at the rate this volume was added, when the physical characteristics of the soils comprising the landfill cap are considered. The response curves of lysimeters 1 and 3 indicated a relatively rapid rise in the storage zone as compared to what would be expected if no preferential flow paths existed, so preferential flow into even these lysimeters is suspected. However, the source of the deep drainage for lysimeters 1 and 3 is limited to the surface area of the lysimeter and its immediate surroundings due to the presence of up-slope barriers. With the large source of water being diverted by the barriers, the resulting positive pressure was small and the responses were limited to those represented in Figures 3.11a and 3.11c.

In contrast, hydrographs for lysimeters 2 and 4 (Figures 3.11b and 3.11d) indicated a rapid rise initially followed by what can perhaps best be described as "direct inputs". In other words, large volumes of deep drainage were piped by the soil profile into the lysimeter storage zone. One possible explanation of these results is that the absence of up-gradient barriers resulted in inputs from up-slope which provided the source of water which in turn provided the source and the head (through ponding) required to facilitate such a rate of response and responses of such magnitude.

It must be noted that the percentage of precipitation data presented in Table 3.2 is not directly applicable to this monitoring period. The reasons for this are quite obvious. First, as described previously, the spring thaw occurred in this period and therefore significant amounts of moisture stored in the frozen soil matrix would have been released adding to the precipitation data. Second, vegetation coverage over the lysimeters was considerably sparser than it was over most of the surrounding area. As a consequence, it is possible that the frost was out of the ground around the lysimeters prior to the rest of the area and that the lysimeters acted as a "sink" collecting melting soil moisture. This process would have had a larger impact on the lysimeters not having up-slope barriers to deflect subsurface flow.

An anomaly is present in the response curve for lysimeter 4 in this period. Between April 3 and 4 the through-cover infiltration accumulating in the storage zone exceeded the storage capacity. As previously reported in section 3.3.5, it is the opinion of the study team that the uppermost effective venting hole is located approximately 20 centimetres above the well bottom. Once the last vent was submerged, It would appear that atmospheric pressure influences resulted In further increases In the recorded data. Consistent with previous experience, the well level dropped as the high pressure passed. This is reflected in the falling response curve values on April 6 and 7. The downward trend stopped just above the 20 centimetre height and subsequently the response curve increased in a very similar manner indicated by lysimeter two's chart when it also filled its effective storage zone.

To help verify the idea that barometric pressures did indeed influence well level readings in lysimeters 2 and 3 when water levels reached a point where efficient gas exchange between the atmosphere and the storage zone was not possible, the storage zones for this period were pumped out and the water volumes in the storage zone were measured using graduated drums. From the calibration curves, total estimated storage volume for lysimeters 2 and 4 are 1050 litres and 1600 litres respectively. Note, in the January-February data however, that barometric pressure influences were becoming quite significant at a well water level of 20 centimetres for lysimeter 4. Lysimeter 2 was fluctuating in the upper portion of the storage zone, but to a much lesser degree than that of lysimeter 4. If it is assumed that lysimeter 2 can be filled to the top of the storage zone while lysimeter 4 can be effectively filled only to the 20 centimetre level, available storage capacity is 1050 litres and 1144 litres respectively. This matches quite closely with the measured volumes pumped out of 1040 litres from lysimeter 2 and 1150 litres form lysimeter 4. Thus, this strongly supports the idea that the response curves for lysimeters 2 and 4 received their shape in part as a consequence of barometric pressure influences.

3.4 Summary of Analysis

As is very evident from a summary of response data presented in Table 3.3, quantitatively the lysimeters do not all respond similarly to individual events, nor are their quantitative monthly responses similar. Even annual responses are unalike ranging from the equivalent of 18 percent to 59 percent of the 12 month precipitation. The reasons for these dissimilarities can to a large part be attributed to the alterations made to some, but not all the lysimeters during the project in an effort to obtain data which seemed reasonable. These changes, while necessary in order to understand the data being obtained and to make the lysimeters more operational, resulted in a group of lysimeters which each responded differently to precipitation inputs. Trends, however, among the more similar lysimeters were noticed (i.e. lysimeters 1 and 3 and lysimeters 2 and 4) as were trends during periods when infiltration levels were so low that the different modifications were not having an influence on the results. For instance, data indicates that lysimeters 2 and 4 both possessed some form of preferential flow path which conducted relatively large volumes of infiltration only when there was sufficient moisture to cause positive pressure resulting from either a build-up of hydraulic head on the ground surface, or the elimination of suction

TABLE: 3.3
SUMMARY OF LYSIMETER RESPONSE CURVE DATA

PERIOD	PRECIPITATION IN PERIOD (mm)	Percent of Precipitation mm of deep drainage			
		LYSIMETER NUMBER			
		1	2	3	4
May - June 1988	64.6	41.8% 27.0 mm	34.1% 22.0 mm	60.4% 39.0 mm	43.3% 27.97 mm
July - Aug. 1988	146.9	2.0 2.9	4.8 7.0	12.3 18.0	3.4 5.0
Sept. - Oct. 1988	138.0	5.8 8.0	5.8 8.0	16.1 22.3	1.6 2.21
Nov. - Dec. 1988	88.8	27.9 24.8	93.5 83.0	73.2 65.0	131.0 116.3
Jan. - Feb. 1989	44.9	7.2 3.23	32.6 14.4	7.2 3.23	26.7 11.98
March - April 1989	77.9	49.1 38.2	134.0 104.4	66.4 51.7	215.0 167.0
Totals (May '88 - April '89)	561.3 mm	18.5% 104.0 mm	42.5% 238.0 mm	35.5% 201.4 mm	59.0% 330.0 mm

pressure, or more likely a combination of both. This is reflected in the data of the monitoring period of November - December and again in March - April. The barriers which were installed for lysimeter 1 and 3 to deflect subsurface run-on achieved their goal very well.

Lysimeter 3 consistently recorded more deep drainage than lysimeters 1, 2 and 4 for the first six months of the monitoring period. One or more of the following reasons could be responsible for this trend:

- surface collection of precipitation into the surface depression directly over the lysimeter leading to enhanced infiltration
- a preferential flow path (possibly associated with the gas transfer tube or surface venting pipe installed in lysimeter 3
- poorly compacted clay in the cap in the vicinity of the lysimeter (i.e. uneven pore space distribution)

Seasonal trends noticed in the data analysis were largely what would be expected, although the magnitude of these trends differ significantly depending on the configuration or modification made to the lysimeter during the study. All lysimeters for example showed summer evapotranspirational demands consumed the stored soil moisture thereby maintaining a high soil storage capacity during these months and reducing the amounts of through-cover infiltration. All lysimeters also indicated that deep drainage quantities were much higher during the late autumn period and spring thaw period than at other times in the year. Through-cover infiltration was found to occur at quite low rates during the winter period.

The analysis of lysimeter operation clearly concludes that the present lysimeters do not respond similarly to precipitation events in the short-term or long-term. This is partially a consequence of the alterations, particularly the installation of up-slope barriers made during the study. Observations made while the alterations were in place have however enabled a better understanding of the factors affecting lysimeter operation. With this knowledge, measures to correct the problems encountered can be incorporated into future lysimeter designs. There are many reasons for the dissimilar response curves within the four lysimeters. In summary, these reasons are:

- poor quality control at the time of installation. The variable compaction, stratigraphy, and depth of materials used from one lysimeter to another gave variations significant enough to induce dissimilar responses from the four lysimeters.

- the fact that lysimeter liners did not extend to the soil surface meant that the partitioning of a subsurface input from surface inputs was not possible. Depressions or "bowls" over the lysimeter, created as a result of differential settlement between the cap directly over the lysimeter and the surrounding landfill cap, provided a collection or storage zone for subsurface run-on water. Different degrees of settlement causing the "bowls" may have resulted in the dissimilar response curves. An inability to fully assess the magnitude of the subsurface run-on component as a source of the total through-cover infiltration, restricts attempts made to determine the influence depressions had on the total water input to the storage zone.

- the installation of barriers up-slope from half of the lysimeters; while providing valuable information, significantly altered these systems and their responses.

- the variability of storage zone porosity naturally affected the shape of response curves (i.e. 37.5 percent for gravel, 82 and 91 percent for drainage tile) but had no obvious affect on infiltration rates.

- the presence of preferential flow paths (i.e. cracks) clearly influenced the response curves. Lysimeter 3 throughout the monitoring period and lysimeters 2 and 4 in the autumn and spring indicated the presence of preferential flow paths.

4.0 SIMULATION TESTING

In an attempt to further access the response characteristics of the installed lysimeters to precipitation inputs, two different types of simulation were performed. Section 4.1 describes a field test which involved simulating rainfall in the vicinity of the lysimeters in order to induce a response and directly observe the collection of water in the storage zone. Section 4.2 on the other hand describes a simulation which involved mathematically modelling the flow of water through the landfill cap in response to precipitation inputs in order to simulate the collection of water in the storage zone.

4.1 Field Simulation

In the spring of 1989 the study team undertook a preliminary field simulation of a precipitation event. The objective of the simulation was to determine if the four lysimeters would respond similarly under a control rainfall condition. An area 5 m x 5 m centred over each lysimeter was delineated. This area was selected because it allowed for a 1 m irrigated border around the lysimeter and the volume of water required for irrigation purposes. The equivalent of a 25 millimetre rainfall was simulated. The simulation was approximately 40 minutes long and was comprised of 2 segments: 23 and 8 minutes in duration, separated by a 9 minute break. The simulation was conducted below the up-slope barriers to remove their effect with respect to run-on.

While totally similar conditions over all lysimeters was desirable it was also impossible to achieve given the time constraints. The field simulation was conducted by applying the amount of water to each lysimeter in the manner described above. The lysimeters were then left undisturbed for 2 days to drain to field capacity. In theory, if all the lysimeters were the same with respect to initial moisture content, density of vegetation, surface configuration and pore space distribution, then the data extracted from response curves would also be the same. However, initial moisture contents varied for each lysimeter and therefore so did the storage capacity. As noted previously, the vegetation coverage over the lysimeter areas was not equal. All these factors contributed to quite unequal initial conditions among lysimeters. Nevertheless, an analysis of the simulation data resulted in the same ranking of lysimeters with respect to the portion of deep drainage captured as was obtained from the full year record. Table 4.1 shows the percentage of simulated precipitation which was captured in the storage zone after 2 days and also after 4 days while Figures 4.1 and 4.2 graphically depict the results of this rainfall simulation on water level in each of the lysimeters storage zones.

FIGURE 4.1: LYSIMETER #1 & #2 - SIMULATION RESPONSE

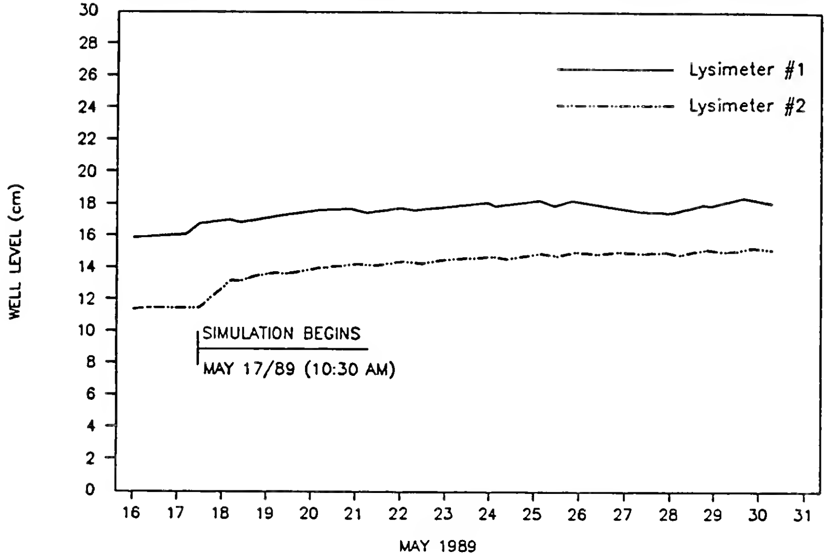


FIGURE 4.2: LYSIMETER #3 & #4 - SIMULATION RESPONSE

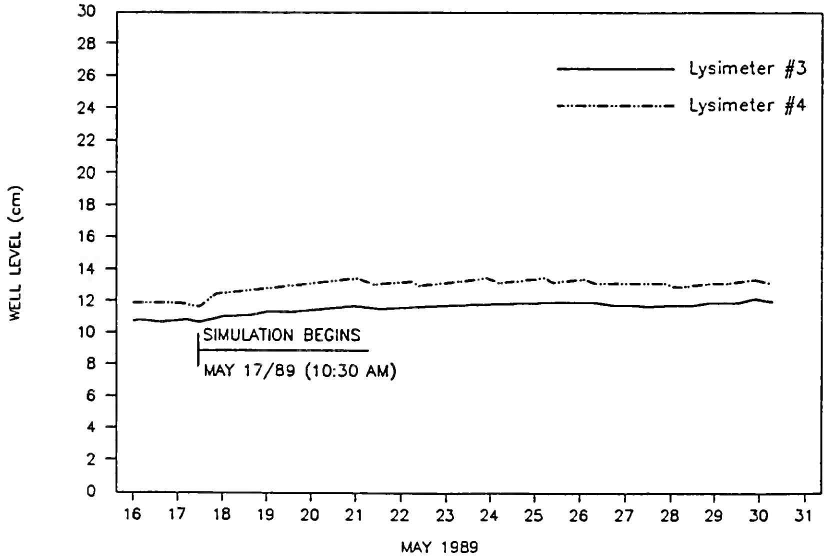


TABLE 4.1
RESULTS OF FIELD SIMULATION

NUMBER OF DAYS AFTER SIMULATED RAINFALL EVENT	PERCENTAGE OF SIMULATED RAINFALL CAPTURED			
	LYSIMETER			
	1	2	3	4
2	8.8	33.0	21.6	42.8
4	10.4	40.4	32.8	46.0

At first glance the lysimeter responses from 25 millimetres of simulated precipitation suggest that possibly the up-slope barriers had less of an effect than previously believed. However, on closer inspection this is not necessarily the case. It is reasonable to assume that initial soil moisture contents reflected the presence or absence of barriers and therefore available storage capacity. The rate of response shown in Figures 4.1 and 4.2 suggest that lysimeters 2 and 4 had higher initial moisture contents and therefore responded rapidly. In contrast lysimeters 1 and 3 had lower moisture contents and therefore were able to store a greater portion of the simulated rainfall. The results of the simulation experiment are inconclusive. However, the simulation exercise served its purpose which was to determine whether the lysimeters responded similarly to a partially-controlled precipitation event and they did not.

4.2 Computer Simulation Modelling

To determine whether the lysimeter response curves possess a shape which is theoretically at least typical of how water is currently thought to move through a clay soil profile, a computer simulation of this process was undertaken. To complete this simulation, the HELP (Hydrologic Evaluation of Landfill Performance) model was employed. HELP is a deterministic quasi-two dimensional model prepared specifically for landfill moisture balances or budgets by the US-EPA that develops a long-term water balance of landfills based on historical or simulated daily rainfall records. It is given the term "quasi" - two dimensional due to the fact that the model's horizontal component of water flow through the soil is not as physically based as is the vertical flow component. Thus the horizontal component is not as genuine as the model's vertical component. While the HELP model is no more complex than a computerized form of a manual tabulation of moisture balance, it combines well accepted state-of-the-art mathematical models for computing an accurate water budget over a variety of climatic, soil and vegetative conditions.

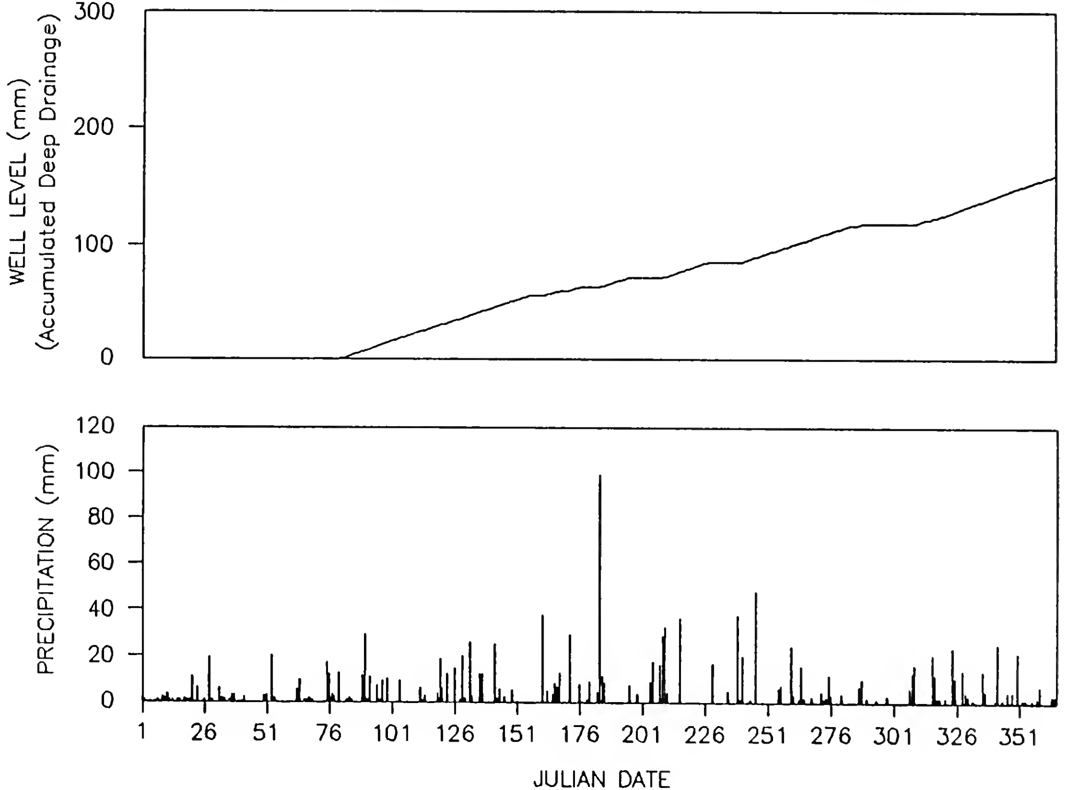
In brief, HELP requests the user to enter daily rainfall and mean monthly climatic records along with a description of the soil or cover profile as input information. The model calculates infiltration through employment of the SCS technique to relate run-off to soil types, land use, soil slope and management

practices using daily rainfall records. A daily inventory of the soil moisture throughout the soil profile is kept using subroutines which calculate daily evapotranspiration and vertical water movement through the soil.

For demonstration purposes, a single year of rainfall data (shown graphically Figure 4.3) was used as the input data to generate a simulated hydrograph through a landfill cap. Input describing the soil profile above the lysimeter storage zone (see Figures 2.2 and 2.3) was also entered. Given that the simulation was for demonstration purposes to note general trends only in a through-cover infiltration curve developed in this manner, readily available rainfall data from Ithaca, New York was used. This US station was selected above other available stations because the size of a 10 year - 24 hour return period storm in Ithaca is quite similar to those experienced in Toronto. As well, the area is subjected to snowfall and freezing temperatures in the winter months. Also, for lack of better data, and to be expedient, soils data used consisted of default values available for the soil textures associated with the various layers of the Britannia Road landfill cover directly over the lysimeters.

Results of the simulation for an entire year can be seen in Figure 4.3. Despite some quite significant rainfall events during the period, the hydrograph showed only a gradual climb in all cases. Given the time required for the infiltrated water to pass through the profile, it is difficult, if not impossible, to detect individual event contributions from the resultant hydrograph with soil storage capacity and evapotranspiration rates playing such a significant role in the entire water budget. As an aside, it was also interesting to note that, while the general shape of this curve is similar to those generated by the lysimeters, the annual quantity of deep percolation is much less at 12.6 percent of the total rainfall while the average for the lysimeters suspected of possessing varying degrees of preferential flow was 38.9 percent of the total annual rainfall. Keep in mind as well that this comparison is between two different sources of rainfall data with the computer simulation year comprising of a total of 1275.8 millimetres precipitation while the Britannia Road site received only 561.3 millimetres of precipitation in the 12 months of study. From this information, one would conclude that the rapid inputs noted in the Britannia Road lysimeters had to result from some form of preferential flow pathway.

FIGURE 4.3: SIMULATED LYSIMETER HYDROGRAPH USING HELP MODEL AND PRECIPITATION INPUT SHOWN



5.0 CONCLUSIONS

To assist in determining the pathways which the water being collected and stored in the lysimeter was following in order to reach the storage zones, barriers were installed up-gradient of two of the four lysimeters under study. This added feature in combination with other lysimeter variables, including the degree of lysimeter and soil settlement creating surface and subsurface depressions atypical of the landfill cover as a whole in the vicinity of the lysimeters, resulted in a dissimilar set of observations for the monitoring year. Consequently, rather than drawing conclusions from the actual infiltration levels which were measured, conclusions instead focuses on how the various lysimeter features affected the through-cover infiltration volumes and rates. Comparing the actual effect of the lysimeter's feature on its performance with the theoretical effect expected, enabled the study team to develop an improved understanding of the operation of the existing lysimeters and make suggestions for their improvement.

It is the opinion of the study team that the primary reason for large differences in the magnitude of infiltration rates measured by each lysimeter can be attributed to the degree at which preferential flow was occurring in the lysimeters in combination with the water supply available for transmission to the lysimeter storage zones. The preferential flow paths that exist are believed to have been supplied with water by surface and subsurface depressions located directly over the lysimeter. Due to the fact that the depressions were always more prominent directly over the lysimeter than they were on the surrounding landfill cap's surface, it was concluded the depressions were created as a consequence of lysimeter and soil settlement and not as a result of the dynamics of the landfill cover in general.

For lysimeters not having up-gradient barriers, the depressions could receive inputs not only from the area immediately surrounding the lysimeter, but could also be supplied by overland and interlayer lateral flow from up-slope areas. Such a large potential water source, when combined with the presence of preferential flow paths, explains not only the volume of infiltration captured, but also the rate at which the infiltration water entered the storage zone. It is the opinion of the study team that, without the presence of a direct path or pipe between the landfill surface and the lysimeter storage zone, lysimeters will <u>not</u> respond immediately to individual precipitation events. Even in a situation where the soil is at or has exceeded field capacity, the response to a rainfall event would be incremented on successive days with the magnitude of each daily "step" in the response being controlled by the saturated hydraulic characteristics of the landfill cap's soil material(s). To expect an immediate response through a uniform soil profile of equivalent magnitude to a precipitation event would be ignoring established soil physical principles.

It is recognized that desiccation cracks most characteristic of fine-textured soils along with those factors which are regarded in agricultural circles at least to improve (influence) soil structure in all mineral soils (i.e. frost action, wetting and drying cycles, earthworm channels, root channels from preceding crops, etc.) can create a series of continuous pores or channels resulting in preferential flow paths. The dry weather period of 1988 for instance could have initiated the development of desiccation cracks. The absence of significant responses in the fall however suggests that, if desiccation cracks were created, they were small and/or did not extend continuously through the clay cap. Soil structural improvements, covered by those factors listed above, on the other hand develop over the long term as seasons pass and organic matter and soil biological activity increases. Given the lack of vegetative cover over the lysimeter areas and the relatively short time span for any structural improvements to have occurred, it is unlikely that significant soil structural improvements have taken place to date as a result of these other influencing factors..

Although, there is no certainty here given a lack of definitive data, observation of lysimeter settlement and the presence of surface depressions would suggest that the preferential flow paths are much more likely to be a consequence of the presence of the lysimeter itself in the landfill cap. With the lysimeter settling, preferential flow paths could be formed around its perimeter. As well, the depressions resulting from settlement could provide the storage and thus supply the water to the preferential flow paths. The outside surface of the monitoring well in the centre of all the lysimeters and the presence of gas venting tubes in lysimeter 3 and surface vents in lysimeter 4 are all quite probable locations for preferential flow paths given the fact that the soil matrix would not easily bind to such plastic surfaces. Even though the bentonite seal was placed along the well it would tend to break contact with the well or pipe wall especially following a freezing and thawing cycle thus permitting flow along the outside of the well casing.

Determining the effect desiccation cracks, soil structural "improvements" and non-uniform landfill cover settlement have on the long-term infiltration rate through a landfill cap is a worthwhile endeavour. To obtain measurements of the effects of these factors, however, requires a reliable and appropriate tool. In order for a 3 metre by 3 metre lysimeter to measure the effects of these factors, the lysimeter must be such that it acts identically to the way the cover would have acted in the area prior to its installation. Even at that, there is no experimental control with respect to how the landfill settles underneath or around it. In other words, is the settlement that is occurring typical of what is happening when the entire cover is considered? Also, time is necessary to evaluate such effects for development of these effects under natural conditions is time-dependent.

It is the study team's opinion, based on observations made, that the present lysimeter requires some modification in order for it to more reliably measure infiltration without its presence in the landfill cover being a significant factor in the measurements it makes. While the response curves presently exhibit the seasonal patterns expected such as higher rates of infiltration during the spring and late fall and little

infiltration during the summer and winter months, the magnitudes of these responses are inconsistent among the lysimeters. The modifications proposed in the following section are steps necessary to address the problems with inconsistencies in lysimeter response found in this study.

6.0 RECOMMENDATIONS

Results obtained through this study indicate that there are numerous areas related to landfilling technology still requiring research, particularly with respect to infiltration through landfill caps. For instance, little is known about the effect differential settlement of a landfill cover has on infiltration as a consequence of the cracks produced in the cover by the settlement. Information is limited on the effects frozen soils and vertical ice lenses have on landfill cover infiltration. The effects of positive gas pressure on moisture infiltration through landfill covers are also to a large extent unknown. Attempts at modelling leachate production at a landfill site cannot be fully developed until such effects are understood. Development and application of a lysimeter capable of measuring these effects on a landfill would be beneficial. A critical aspect of this lysimeter is that it must be capable of being an indiscriminate part of the landfill cap so as not to significantly affect the measurement of infiltration, but rather be representative of the cover system. In order for the present lysimeter to potentially fulfil these high demands as a tool for measuring infiltration through landfill covers, a number of weaknesses in their design and construction first need to be addressed. In general, these weaknesses are as follows:

1. The storage zones are not sensitive enough to through-cover infiltration inputs on a daily or event basis. This has an affect on both the desired measurement and calibration accuracy.

2. Materials in the storage zone do not facilitate quick draining and thus hamper the procedure of pumping the storage zone as well as directly measuring volumes of deep drainage stored.

3. There is insufficient air/gas exchange between the storage zone and the atmosphere.

4. The level of care and detail adhered to at time of construction needs to conform to the level of detail that is necessary to achieve the demands placed on the lysimeter as a measurement tool.

5. The current lysimeter design is susceptible to the creation of preferential flow paths.

To overcome these weaknesses in the current prototype, it is proposed the lysimeters incorporate the concepts outlined below:

1. Modify the storage zone and/or modify the measurement expectations of the lysimeter. Two concepts are implied with this suggestion. One idea entails modifying the storage zone so that it is deeper and filled with material that is much less porous while at the same time maintaining storage zone uniformity. Such a storage zone which is less porous yet facilitates rapid recharge would make the water level in the storage zone more sensitive to infiltration inputs. In this way

the water level recorder could better detect small additions of water to the storage zone, perhaps even on a daily or "infiltration event" basis.

The second concept involves modifying or relaxing the expectations of the data to be collected. For instance, if a record of monthly or annual amounts of through-cover infiltration is really all that is desired, then simply a monthly pump-out and direct volumetric measurement of the infiltration water collected in the storage zone for that period would be the most efficient monitoring approach. Note even here however, that the storage zone would need to enable rapid recharge to the well for pump-out purposes.

2. Vent the lysimeter storage zone through the lysimeter well to encourage and ensure a rapid gas exchange. Unfortunately, with venting, monitoring any possible effects of landfill gas pressure would be lost unless an approach other than the use of a float-activated chart recorder was taken to monitor lysimeter storage volumes. Measurement of landfill gas effects would require more complexity. It would involve first, connecting the lysimeter storage zone to the outside gas in the landfill. Then, with the storage zone vented to the interior of the monitoring well, the water level measuring device would need to be sealed inside the well to prevent the escape of gas to the atmosphere.

3. Install the lysimeters in such a manner that the probability of development of any preferential flow path along the soil-lysimeter interface is minimized.

4. Develop and follow a detailed protocol for lysimeter installation that matches the care and attention to detail necessary for such an application. Each step of the installation procedure should be outlined prior to field installation. This is included as a means of ensuring the landfill cover over the lysimeter is as close a match as possible to the surrounding undisturbed cap.

6.1 Lysimeter Design Recommendations

The drawing presented in Figure 6.1 illustrates modifications which could address the weaknesses associated with the present lysimeters yet not entail a significant change in the base concepts used in this prototype. A flexible liner will still form the storage zone in order to accommodate landfill movement. The depth of storage zone will increase and the storage medium used will be less porous than what exists in the present lysimeters to improve the sensitivity of the storage zone. In order for the storage zone to accommodate a year of infiltration and yet provide the measurement sensitivity needed, it is recommended the storage zone be at least 1 m deep, this is assuming a 25% porosity of the storage medium.

In order to obtain daily "trends" in through-cover infiltration rates and yet avoid the expense and complications suspected to be involved with developing a more sensitive and rapidly recharging storage zone, it is proposed a compromise be made between the two approaches. The suggested storage zone will consist of large diameter, highly porous plastic drainage pipe allowing for the efficient monthly pumping out of the storage area for volumetric measurement purposes. A float-activated chart recorder will also be installed to monitor the relative timing of when the volumetric-measured infiltration water entered the storage zone during the month.

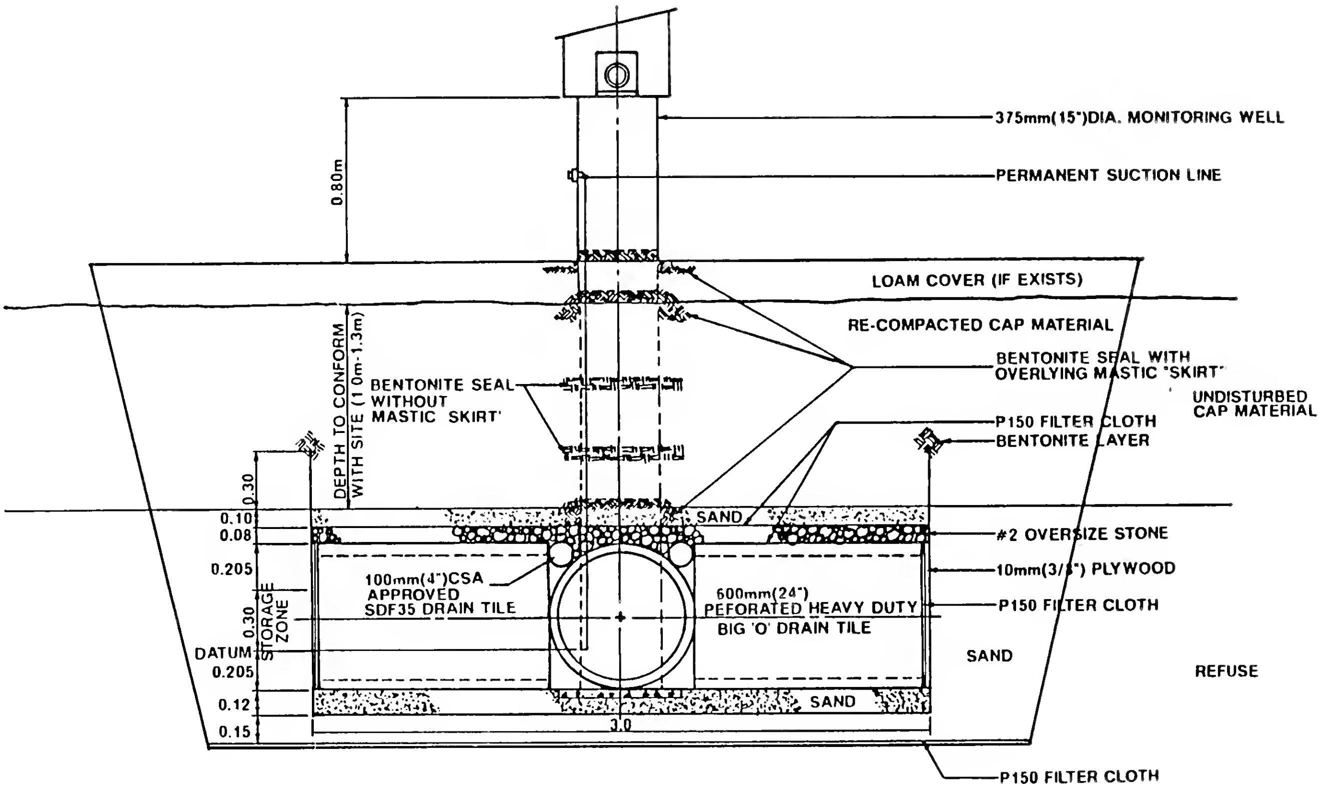
Large diameter Big "O" perforated heavy duty drainage pipe is suggested for the storage zone for its light weight and strength characteristics. A zero datum would be selected slightly above the bottom of the storage zone to avoid complexities associated with changes in storage zone mediums. Water added to reach the zero datum will also add sufficient weight to the lysimeter to have it approximate (on average as a unit) the density of the surrounding garbage and cap material.

The lysimeter liners will extend only 0.3 metres into the landfill cap. With such a layout, a more representative measurement of through-cover infiltration is possible, given that all sources and losses of water having potential to reach the storage zone are accounted for. At present, it is unknown what proportion of infiltration water enters and leaves the lysimeter area below the cap's surface. Only eliminating this unknown by extending the liner to the surface and comparing this lysimeter's results with another lysimeter whose liner is below the surface would begin to answer this question. The key to obtaining the improved representativeness of the lysimeter whose liner is below the surface will be our ability to re-construct the cap in the excavated area to match as closely as possible the surrounding undisturbed landfill area. The presence of foreign sand layers integrally associated with the lysimeter design in the excavated zone raises questions as to the possibility of achieving the necessary similarity.

Given the limitations associated with both approaches, the best which can be done is to take the necessary precautions to prevent foreseen problems with the shorter wall, such as preferential flow of subsurface water along its interfaces. Even if a comparison of inputs between a liner extending to the surface and one below the surface were to be made, confidence in the functioning suitability of both lysimeter configurations would be needed. Since being able to partition the source components is not necessary, a design that facilitates this is redundant.

Besides the liner height and storage zone characteristics, other modifications need to be considered. Collars on skirts around the outside of the monitoring well will break the development of preferential flow paths in this area. The monitoring well will be slotted to allow for gas exchange. The monitoring well will provide access to the storage zone for times when the zone needs to be pumped out for the direct measurement of the water volumes stored. It will also provide a means of monitoring the storage zone water depth through the use of an economical float-activated chart recorder. Monitoring of the effects of positive gas pressure on infiltration is not possible with the layout described. Only an enclosed system

FIGURE 6.1: Concepts Recommended for Incorporation into Future Installations



incorporating permanent pumping apparatus and an electronic means of measuring water depth would be capable of this. Finally, great care will be required in the construction of the lysimeters to return the cover as near as possible to the condition it was prior to lysimeter installation. It is also recognized that construction protocol for a lysimeter may have to include one or two returns to the lysimeter following a period of settlement and frost action to ensure the lysimeter areas match the surrounding topography.

It is emphasized that these ideas are conceptual. It will require the knowledge and experience of all involved in future installations to arrive at specific designs, materials and installation procedures most suitable and economical for the application.

APPENDIX A

Construction of Lysimeters at Britannia Road Landfill

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CONSTRUCTION OF LYSIMETERS

AT BRITANNIA ROAD LANDFILL

Construction of the lysimeters began at 8:00 a.m. on August 10, 1987 at Britannia Road Landfill, located at Britannia Road and Second Line in Mississauga.

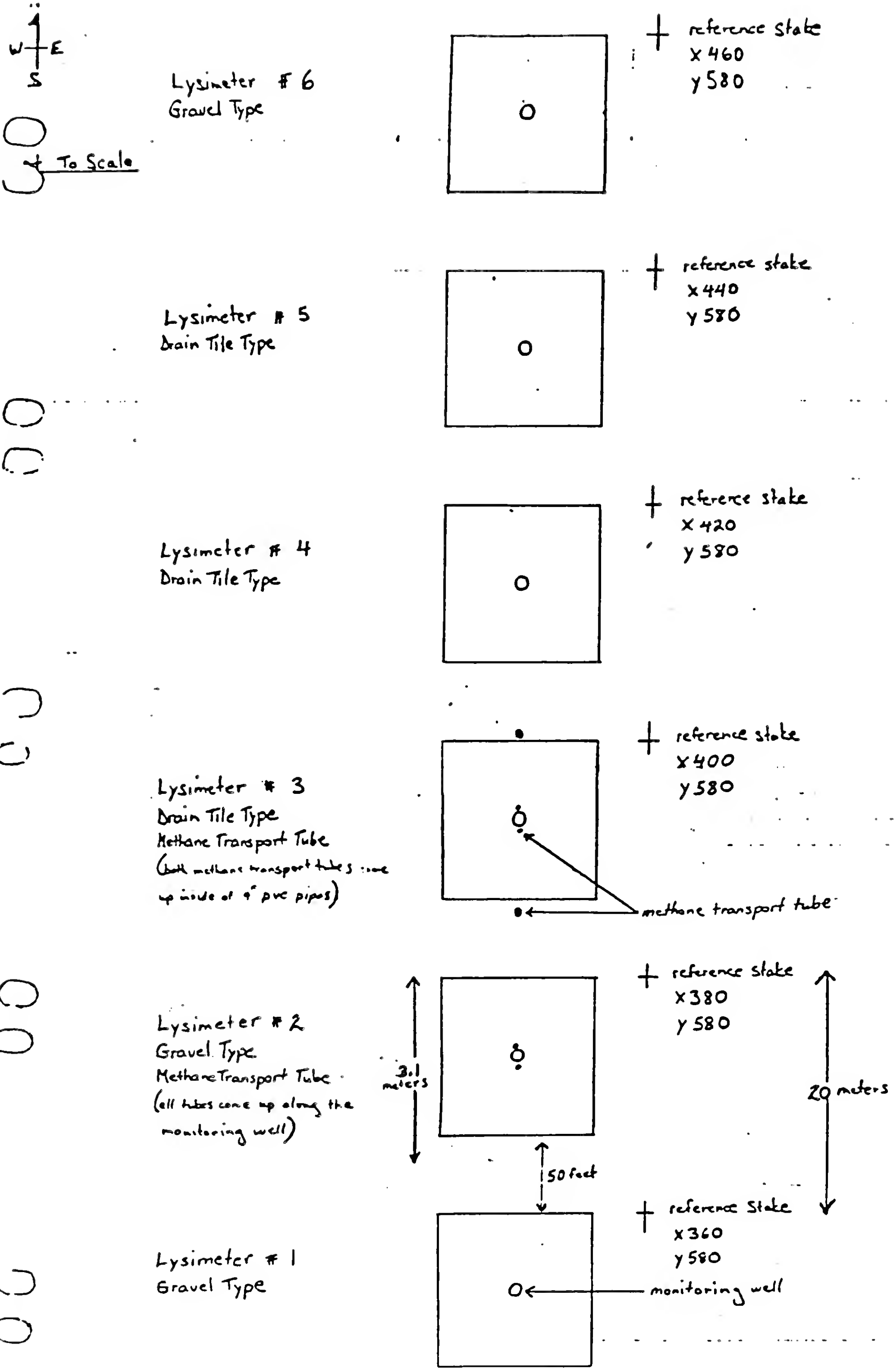
The area designated for the six lysimeters is in the southwest corner of the landfill. The 120 meter strip of land is situated in a predominantly north-south direction and has a very gentle slope to the west. Construction began by excavating six holes 4.6 metres x 4.6 meters x 1.5 meters with a backhoe. This part of the project took approximately 2.5 days to finish. Each hole was surveyed using a survey transit to ensure that the bottom was level. The clay cover that was excavated was piled on one side of the excavation and the excavated solid waste was piled separately on another side. The solid waste was removed the next day and landfilled. The piled clay was used for cover material over the lysimeters.

Each lysimeter was positioned so that its northeast corner was several feet from a survey stake. Each survey stake had co-ordinates marked on it from which contours can be obtained. The survey stakes are approximately 20 meters apart, therefore, the distance separating the lysimeters is approximately 15 meters (see figure 1).

After the lysimeter pits were finished, construction of each lysimeter began by placing a 4.6 meter x 4.6 meter sheet of filter cloth on the bottom of the pit and covering this with six inches of sand. The sand was compacted by the backhoe and by foot. Originally, two tampers were called in to tamp the sand layer but the tamper displaced the sand rather than compacting it, therefore, they were not used. Once compacted, the sand layer was checked to ensure it had a level surface.

The flexible membrane liner (93 mil thickness) was unrolled in the pit, and centered. It was received from the manufacturer pre-formed in the shape of a box with dimensions 3.1 metres x 3.1 meters x .91 meters. One wooden stake was driven into the sand at each corner of the liner. Two-by-fours were used to construct the frame from which the liner would hang. Three meter lengths of two-by-fours were nailed to the wooden stakes .91 metres above the top of the sand. The entire wooden frame was checked to ensure that the lysimeter would be completely level.

The top of the liner was pulled up to the wooden frame .91 meters off the bottom and attached securely by 1/4 inch roofing nails. The liner was positioned on the frame loosely to prevent tearing due to differential settlement of the garbage below.


N
W
E
S
To Scale
Lysimeter # 6
Gravel Type
reference stake
x 460
y 580
Lysimeter # 5
Drain Tile Type
reference stake
x 440
y 580
Lysimeter # 4
Drain Tile Type
reference stake
x 420
y 580
Lysimeter # 3
Drain Tile Type
Methane Transport Tube
(both methane transport tubes come up inside of 4" pvc pipes)
reference stake
x 400
y 580
methane transport tube
Lysimeter # 2
Gravel Type
Methane Transport Tube
(all tubes come up along the monitoring well)
3.1 meters
reference stake
x 380
y 580
20 meters
50 feet
Lysimeter # 1
Gravel Type
reference stake
x 360
y 580
monitoring well

Once the liner was in place, a 15 cm layer of sand was placed inside the liner. The area outside the lysimeter was filled simultaneously with the interior to ensure the liner walls maintain a vertical position. Once the sand layer was completed to the appropriate thickness and levelled off, a 1/2 inch piece of patio stone .61 meters x .61 meters was centrally placed 7.5 centimeters deep. The patio stone was then checked to ensure it was level.

A piece of filter cloth 3.4 meters x 3.4 meters was placed over the sand layer and the patio stone. The 35.6 centimeter diameter monitoring well was centered on the patio stone above the filter cloth. The monitoring well was checked with a level to ensure it was perfectly vertical.

At this point in the construction the remaining material that went into the lysimeter depended on the lysimeter type. The two types of lysimeters installed were gravel and drain tile. The gravel lysimeter required 30cm of gravel to be placed within the lysimeter. The drain tile type required two layers of slotted drain tiles (10.2 centimeter diameter) to be placed horizontally within the lysimeter. The second "layer" of tiles were placed 90 degrees to the first layer. The space between the drain tiles and the monitoring well was filled in with gravel up to the second layer of tiles.

Filter cloth was placed over the gravel or drain tiles depending on the type of lysimeter installed. A slit was cut in the filter cloth to allow it to slip over the monitoring well. A 15 cm sand layer was placed on top of the filter cloth and compacted by foot. The top of this sand layer is approximately .32 to .61 meters below surface. The area chosen for the lysimeter construction is receiving an additional .61 to .91 meters of clay cover. This will bring the total thickness of cover material being monitored by the lysimeters to approximately 1.2 meters.

Two methane transport tubes were installed, one in each type of lysimeter. These tubes were constructed by placing a 30 cm section of 1/4 inch slotted pvc pipe, wrapped in filter cloth, into the solid waste layer at the bottom of the pit horizontally. An elbow was glued onto the end of the pipe that was protruding from the solid waste layer. A 1.5 meter section of pvc was attached onto the elbow extending to the surface. A 1.2 meter section of pvc pipe (1/4 inch diameter) was then placed vertically in the lysimeter so that the bottom of the pipe was situated in the upper sand layer. This pipe extends to surface and is connected to the pipe that leads into the garbage. The connection has a valve and 2 pressure ports which are located above surface. This provides the necessary conduit for gas to migrate into the top sand layer below the clay cover. The valve and 2 pressure ports allow the inside and outside lysimeter gas pressures to be monitored.

The recompacted clay is placed into the lysimeters in approximately 15 to 20 centimeter lifts which is then compacted using a pneumatic vibrator attached to the backhoe. Each lysimeter was tested for compaction using a nuclear densitometer. The results of compaction ranged from 95 to 100% standard proctor density. Bentonite was placed around the monitoring well in both lifts to prevent vertical migration of water along the sides of the well.

RECOMMENDATIONS FOR FUTURE LYSIMETER CONSTRUCTION

The wooden frames constructed inside each excavated lysimeter pit could have been pre-constructed. The liner could then be placed onto the frame and attached with nails. The entire construction could then be placed into the excavated pit as one complete unit and then levelled off accordingly.

The addition of a valve and two gas ports in the design of the methane transport tube eliminates the need for a gas probe. The inside lysimeter gas pressures can be measured directly from the pressure ports.

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APPENDIX B

Calibration Data

FIGURE B1: CALIBRATION CURVE FOR LYSIMETER #1
(GRAVEL TYPE)

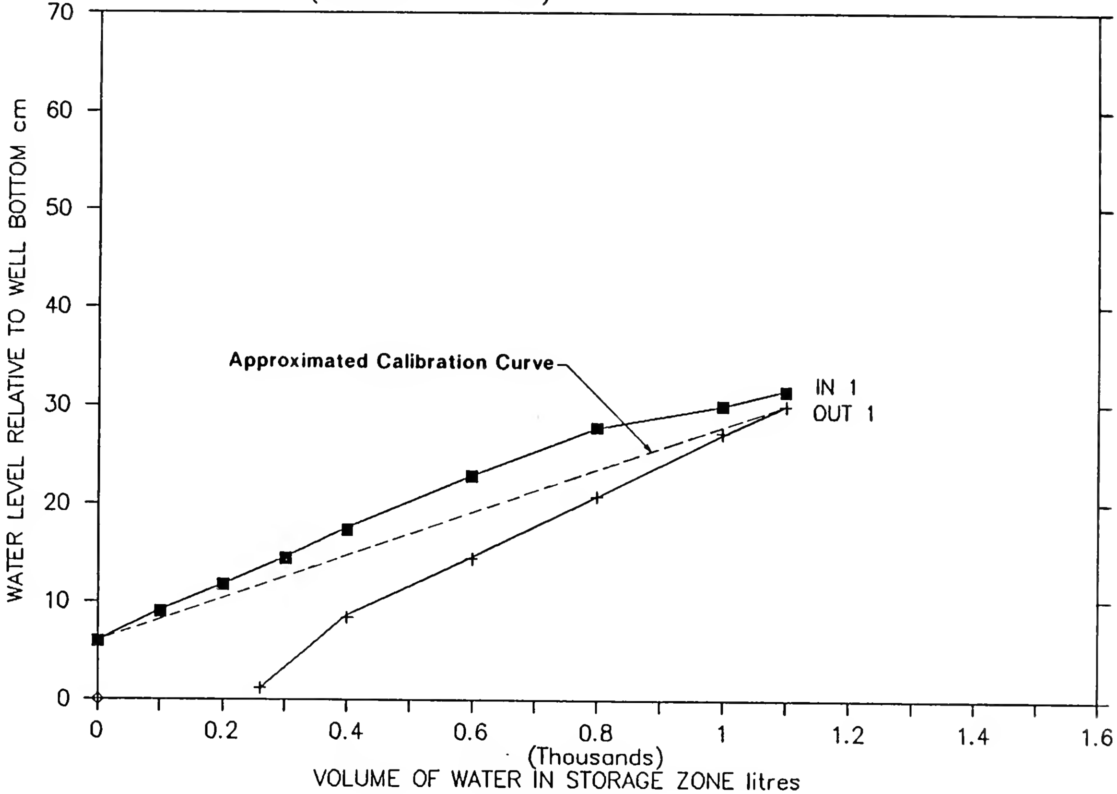


FIGURE B2: CALIBRATION CURVE FOR LYSIMETER #2
(GRAVEL TYPE)

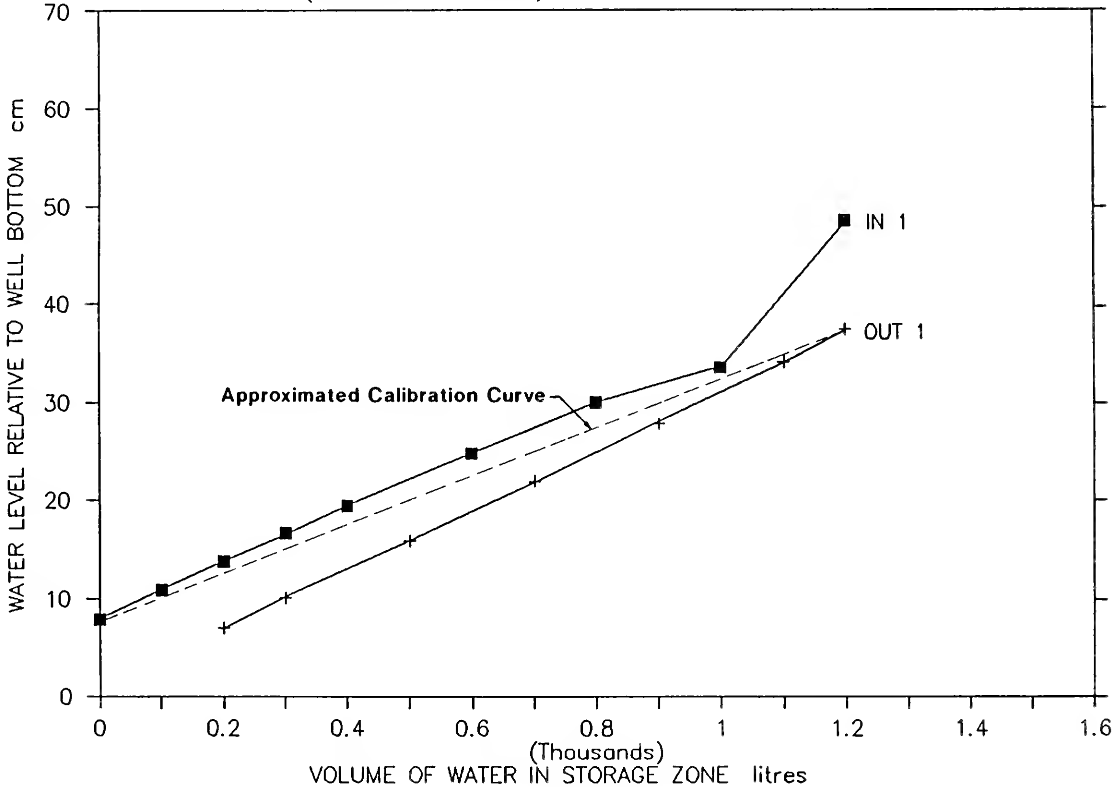


FIGURE B3: CALIBRATION CURVE FOR LYSIMETER #3
(DRAIN TILE TYPE)

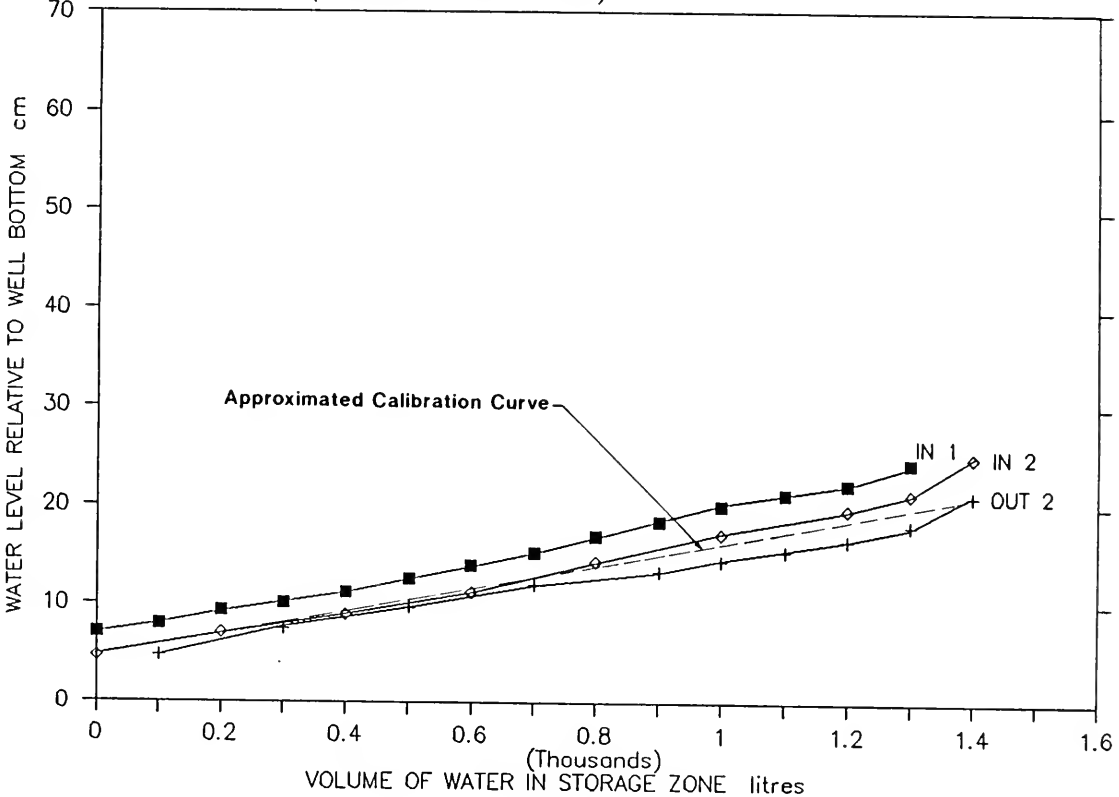
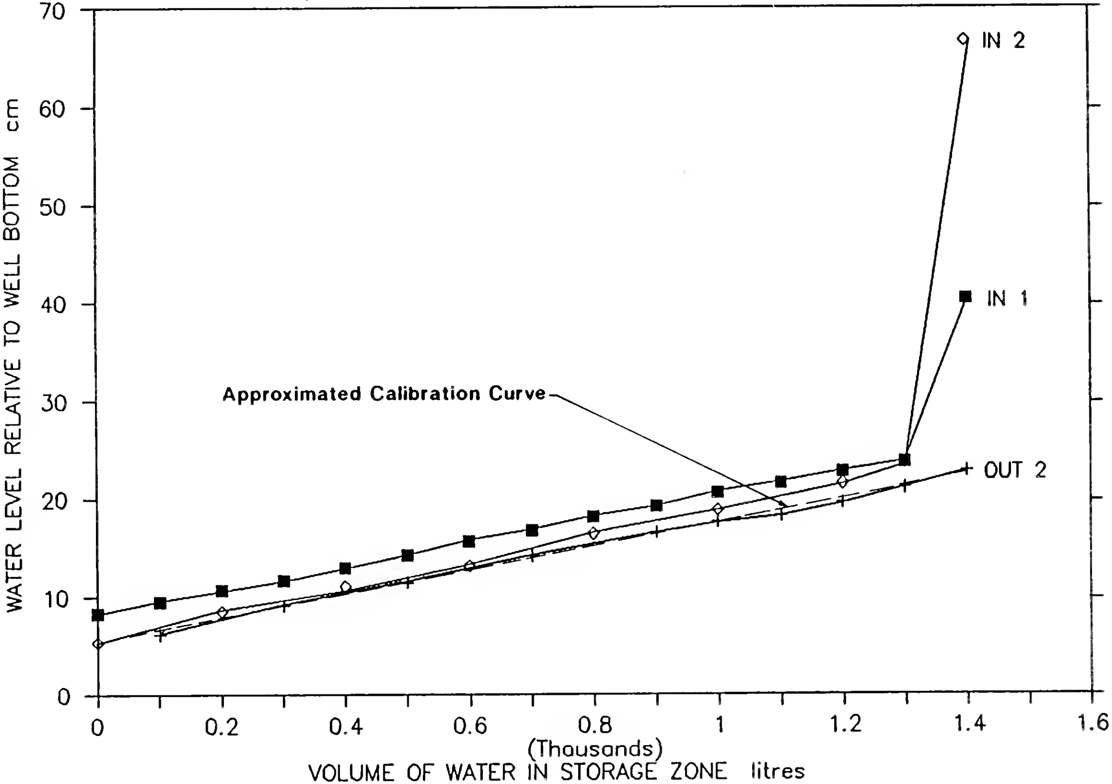


FIGURE B4: CALIBRATION CURVE FOR LYSIMETER #4
(DRAIN TILE TYPE)



APPENDIX C

Detailed Stage Recorder Graph Data
(November 23, 1987 to May 30, 1989)

(FLOPPY DISKETTE)

Appendix C

Detailed Stage Recorder Graph Data
(November 23, 1987 to October 31, 1989)

For ease of presentation, all stage recorder graphs were transferred to Lotus spreadsheet form. Each lysimeter has a spreadsheet associated with it, with the worksheet files named as follows:

Lysimeter 1 Data - LYSIDAT.WK1
Lysimeter 2 Data - LYS2DAT.WK1
Lysimeter 3 Data - LYS3DAT.WK1
Lysimeter 4 Data - LYS4DAT.WK1

These files are on the floppy diskette enclosed.

Access to these files is possible through the utilization of the popular software package, Lotus 1-2-3. For details concerning how the spreadsheet is set-up, refer to Ecologistics (1989) report entitled -- Erosion of Municipal Solid Waste Landfill Covers. The spreadsheet column titles are also quite self-explanatory.

A P P E N D I X D

Randomized Block Analysis -- Comparison Among Means

Appendix D

Randomized Block Analysis -- Comparison Among Means

The following details the statistical analysis conducted to determine if the difference in means between the four lysimeters is significant.

In particular, the purpose is to determine whether the presence of up-gradient barriers had an effect on infiltration to a greater degree than can be explained simply due to non-homogeneity of the site.

The randomized block diagram in Table D.1 summarizes the percent infiltration data being used in the analysis and includes necessary totals and means used in the calculations.

Lysimeter Number	May-June	July-Aug.	Sept.-Oct.	Nov.-Dec.	Jan.-Feb.	Mar.-Apr.	Total	Mean
1	41.8	2.0	5.8	27.9	7.2	49.1	133.8	22.3
2	34.1	4.8	5.8	93.5	32.6	134.0	304.8	50.8
3	60.4	12.3	16.1	73.2	7.2	66.4	235.6	39.3
4	43.3	3.4	1.6	131.2	26.7	215.0	421.2	70.2
Total	179.6	22.5	29.3	325.8	73.7	464.5	1095.4	

Given that the primary purpose of the test is to determine if the up-gradient barriers are causing the lysimeters with barriers to act differently from those which do not. It is necessary to remove from the population those observations in which the barriers would not have been needed because surface runoff is negligible. This would result in the removal of data for the months of July to October when evapotranspiration is at its peak and for the winter period of January and February when frozen soils result in no surface runoff. Thus, the revised randomized block diagram used in the analysis is as follows:

Lysimeter Number (BLOCK)	PERCENT INFILTRATION COLLECTED — TWO MONTH PERIOD (TREATMENT)				
	May-June	Nov.-Dec.	Mar.-Apr.	Total	Mean
1	41.8	27.9	49.1	118.8	39.60
2	34.1	93.5	134.0	261.6	87.20
3	60.4	73.2	66.4	200.0	66.67
4	43.3	131.2	215.0	389.5	129.83
Total	179.6	325.8	464.5	969.9	

A summary of the necessary values for calculation purposes follows:

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square
Treatment	2	10 148.31	5074.16
Block	3	13 027.22	4342.41
Residuals (Error)	6	9 958.48	1659.75
Total	11	33 134.01	

Have three treatments with s = 969.9 = 31.14 (6 d.f.)

Using a t-distribution and confidence limit of 95%: the variance on the entire sample is:

31.14/2 = 15.57

For six degrees of freedom, the largest difference between the means allowable for the lysimeters to be considered the same is:

2.447 (15.57) = 38.1

The following lists the difference between the means.

Difference between lysimeters 1 and 2 = 87.2 - 39.6 = 47.6 > 38.1
Difference between lysimeters 1 and 3 = 66.67 - 39.6 = 27.07 < 38.1
Difference between lysimeters 1 and 4 = 129.83 - 39.6 = 90.23 > 38.1
Difference between lysimeters 2 and 3 = 87.2 - 66.7 = 20.53 < 38.1
Difference between lysimeters 2 and 4 = 129.83 - 87.20 = 42.63 > 38.1
Difference between lysimeters 3 and 4 = 129.83 - 66.67 = 63.16 > 38.1

These results indicate that lysimeters 1 and 3 could be considered as being similar as could lysimeters 2 and 3. There does not exist however 3 lysimeters that could be considered being similar. Note that those lysimeters with barriers were determined to be similar. Thus comments on observations by individual lysimeter and comparisons among results of lysimeters 1 and 3 and 2 and 3 only are possible.

A P P E N D I X   E

Maximum, Minimum and Mean Daily Temperatures
(March - April, 1989)

FIGURE E1: MAXIMUM, MINIMUM AND MEAN DAILY TEMPERATURE FOR MARCH/APRIL 1989